Well Pattern Modification and Injection-production Optimization for Extra-high Water Cut Oilfield

Renyuan Sun1,2, Yu Chen1,2, Yingsong Huang3, Gang Cao3, Aixian Huang4, Lijie Liu3 and Zhihong Liu3

1School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, Shandong 266580, China
2Key Laboratory of Unconventional Oil and Gas Development of Ministry of Education, Qingdao, Shandong 266580, China
3Research Institute of Petroleum Exploration and Development, Shengli Oilfield Company, Dongying, Shandong 257000, China
4Dongxin Oil Production Plant, Shengli Oilfield Company, Dongying, Shandong 257000, China

Abstract. The extra-high water cut stage is still an important stage of oil production. In order to develop the oilfield in this stage, a reservoir model was established using the geological and production history data of a block in Shengli Oilfield. Based on the history matching result, the numerical reservoir simulation of the modification was carried out from row injection well pattern to different well patterns. On the basis of residual oil distribution, balanced injection-production and formation pressure distribution, the optimal well pattern for this block was optimized. The well spacing for different well pattern was also simulated. The optimal well spacing was determined by the net present value (NPV) method, and the timing of well pattern modification was determined by the relationship between NPV peak and water cut. Latin hypercube sampling method was used to design the injection-production parameter schemes. The optimal injection and production parameters range of row and nine point well pattern was determined respectively. This research results can be used for reference in the development and adjustment of similar oilfields in the extra-high water cut period.

Keywords: Extra-high water cut; well pattern modification; injection and production optimization.

1. Introduction

The development of oilfields in extra-high water cut period is one of the severe challenges in the sustainable development of oilfields. There are both high water content areas in the direction of high permeability [1,2] and residual oil rich local areas in the reservoir. The sweep efficiency of injected water is reduced, and the residual oil is difficult to produce effectively. The problems of interlayer interference, imperfect well pattern and imbalance displacement are serious [3-5]. Conventional measures are difficult to meet the requirements of stable oil production and enhance oil recovery. Therefore, how to establish effective displacement between injection-production wells and improve development effects has become an important research issue.

In recent years, many experts and scholars have also proposed specific well patterns modification and injection-production optimization schemes for different oil fields [6-8]. Development practice shows that well pattern modification and injection production optimization are important measures to increase...
the sweep efficiency of injected water, slow down the rising rate of water cut, and enhance oil recovery [9-10] in extra-high water cut period. Taking an extra-high water cut block of Shengli Oilfield as the research object, the numerical simulation study on the modification of row well pattern to different well patterns, row well spacing optimization and injection-production optimization in row and nine point well patterns were carried out. Base on the simulation results, the best well pattern modification mode for the block, the optimal well spacing range of the well pattern, and the optimal range of injection production parameters that could maximize the economic benefits were determined. The results have important reference significance for the development and adjustment of similar oil fields in the extra-high water cut period.

2. Reservoir Construction
The target block is located in Shengli Oilfield. Its average depth is 1250 m, the initial reservoir pressure is 12.71 MPa, the area is 1.44 km², the effective thickness of the reservoir is 10m, the average permeability is $1000 \times 10^{-3} \mu m^2$, and the average porosity is 0.25, the irreducible water saturation is 0.33. The crude oil has a volume coefficient of 1.088, a density of 0.89 g/cm³, and a viscosity of 37.1 mPa·s under the bubble point pressure of 10.62 MPa, and has a density of 0.95 g/cm³ and a viscosity of 1068 mPa·s under the ground pressure. The reservoir is a closed reservoir without side water, which is produced by a row wells pattern with 300m×300m well spacing. Maintaining the IWR (injection-withdrawal ratio) of 1:1, after 30 years water flood development of the reservoir, most of the current residual oil is concentrated on both sides of two oil well rows in the upper layer, and the bottom layer is almost completely water flooded. The cumulative recovery degree is 50.44%, the composite water cut reaches 97%, and the average formation pressure is reduced by 0.65 MPa.

3. Well Pattern Modification
At present, the well pattern used in this block is a square row well pattern, it can be converted into five point, square seven point, nine point, anti-seven point and anti-nine point well pattern. Therefore, five well pattern modification schemes were designed based on the principle of maximizing the use of current injection and production wells. Maintaining the IWR of the whole reservoir at 1:1, and the development simulation of different well patterns was carried out for 15 years. Compared all schemes results shown in Figure 1, only the nine point well pattern has a higher cumulative oil production than the row well pattern, and the cumulative production degree is increased by 6.42%, which is 1.30% higher than the initial row well pattern, while the development effect of other well patterns is not as good as the initial row well pattern.

Figure 2 is a diagram of the modification of row well pattern to the nine point well pattern. Comparing the distribution of residual oil saturation in the nine point well pattern with the row well pattern before conversion, the nine point well pattern can improve the reservoir seepage field, effectively drive the residual oil between wells, improve the sweep efficiency of injected water, and the effect of balanced injection in each area is better. Therefore, the nine point well pattern is selected as the best well pattern.

4. Well Spacing Optimization
In actual reservoir production management, NPV (Net Present Value) method is commonly used to evaluate the economic benefits of water flood development reservoirs [11]. Therefore, the objective function of well spacing optimization is,

$$ NPV = OP \times FOPT - WIC \times FWIT - WTC \times (FLPT - FOPT) - DC \times i - OIC \times n $$

Where, $NPV$ is the net present value, CNY; $OP$ is crude oil price, CNY/t; $FOPT$ is cumulative total oil production, sm³; $WIC$ is water injection cost, CNY/t; $FWIT$ is cumulative total water injection, m³; $WTC$ is water treatment cost, CNY/t. $FLPT$ is the cumulative total liquid production, sm³; $DC$ is the drilling cost, CNY/well; $i$ is the number of wells drilled under a certain well spacing; $OIC$ is auxiliary investment costs, CNY/year; $n$ is development years.

Five row well patterns with different well spacing (1200m, 600m, 300m, 200m and 150m) were designed for the block, and the IWR of the whole reservoir was maintained at 1:1 for development
simulation. The change of NPV with development time at each well spacing was calculated. According to the results shown in Figure 3 and Figure 4, the peak value of NPV increases first and then decreases with the increase of the well spacing, so the optimal range of well spacing is 300m-600m. The development time corresponding to the NPV peak increases linearly with the increase of the well spacing, which means the smaller the well spacing is, the less time it takes for the oil field to recover the investment. The average water cut corresponding to the NPV peak hardly changes with the well spacing, about 86.2% in this block, indicating the well patterns with different well spacing can change the reservoir management mode under the same water cut conditions to increase the benefit of reservoir development. The results can be provided as research basis for timing of well pattern modification with different well spacing or injection-production optimization.

Figure 1. Comparison of cumulative oil production of all well patterns modification schemes.

Figure 2. Diagram of the modification of row well pattern to the nine point well pattern.

Figure 3. Effect of well spacing on the value of NPV peak and its development time.
5. Injection-production Parameters Optimization

5.1. Row Well Pattern
Latin hypercube sampling (LHS) [12] method is used to design the schemes of this block. The advantage of LHS method is that it can guarantee the independence of the selected variables and the uniformity and randomness of the spatial distribution. Ten Latin hypercube random schemes after screening (0.8 < IWR < 1.2) are designed by LHS method. Comparing the simulation results of cumulative oil production (Figure 5) and composite water cut (Figure 6) of each scheme, it can be concluded that the scheme Row4 has a significantly better oil production increase effect than other schemes, and scheme Row6 and Row1 has an obvious effect of reducing and controlling water cut. Therefore, if the main goal is to reduce and control water cut, and achieving a certain degree of oil increase effect, it is better to choose Row1 and Row6 schemes. If the main goal is to increase oil production, and control the rise of water cut, schemes Row4 and Row2 are better, especially scheme Row4 has the highest oil production while has a better effect of controlling the rising speed of water cut.

Figure 5. Comparison of cumulative oil production in the schemes of row well pattern.

Figure 6. Comparison of composite water cut in the schemes of row well pattern.
5.2. Nine Point Well Pattern
The nine point well pattern schemes design was carried out by using the LHS method. Nine Latin hypercube random schemes after screening (0.8 < IWR < 1.2) are designed. Comparing the simulation results of cumulative oil production (Figure 7) and composite water cut (Figure 8) of each scheme, it can be concluded that the schemes Nine2, Nine7 and Nine9 have a significantly better oil production increase effect than other schemes, while scheme Nine1 is effective in reducing and controlling water cut. Therefore, if the main goal is to reduce and control water cut, and achieving a certain degree of oil increase effect, scheme Nine1 is a better option. If the main goal is to increase oil production, and control the rise of water cut at the same time, schemes Nine2, Nine7 and Nine9 can be used. While the IWR of the scheme Nine7 is close to 1, so the effect of slowing down the formation pressure drop is better.

![Figure 7. Comparison of cumulative oil production in the schemes of nine point well pattern.](image)

![Figure 8. Comparison of composite water cut in the schemes of nine point well pattern.](image)

6. Conclusions
(1) Based on comprehensive consideration of residual oil production effect, reservoir balanced injection-production effect and formation pressure distribution, the nine point well pattern is determined as the best well pattern that can be converted by the current row well pattern in this block.
(2) The water flood development simulation of the row well pattern under different well spacing (1200m, 600m, 300m, 200m and 150m) was carried out. The optimal well spacing range was determined to be 300m-600m with the NPV as the objective function of well spacing optimization. The timing of well pattern modification or injection-production optimization is proposed according to the relationship of NPV peak and water cut.
(3) Latin hypercube sampling method was used to design the injection and production parameter schemes, and the specific parameters range is obtained as follows: for the row well pattern, the injection rate of the side row water wells is 23-30 m³/d, the center row water wells is 17-22 m³/d, and the fluid production rate of oil wells is 35-45 m³/d; for the nine point well pattern, the injection rate of the corner
wells is 13-20 m³/d, the borderline wells is 13-15 m³/d. and the fluid production rate of oil wells is 90-97 m³/d.

Acknowledgements
The work is supported by the National Science & Technology major Project of China (No. 2016ZX05011-001) and Program for Changjiang Scholars and Innovative Research Team of China (No. IRT1294).

References
[1] Zhou P, Chen M, Feng X U, et al. Establishment and Application of New Water Drive Characteristic Curve at High Water cut Stage[J]. Xin-jiang Petroleum Geology, 2014, 35(03):329-332.
[2] Zhou Weidong, Dou Zhilin, Sun Xiaoyan. Optimization and adjustment of water injection and fluid production structure in super high water cut period in Gudong oil field [J]. Oil & Gas Recovery Technology, 2000, 7(02):27-29+2.
[3] Wen H, Liu Y, Sun N. A new water drive curve at extra-high water cut stage and application in prediction of oilfield development [J]. Journal of Petroleum Exploration & Production Technology, 2017, 7(4):1113-1123.
[4] Huang Yingsong. Waterflooding Performance of Oil Reservoir in Extra-High Water cut Stage [J]. Special Oil & Gas Reservoirs, 2018, 25(01):95-99.
[5] Chen Li. Reach about Well Pattern and Injection-production Parameter Boundaries of Reservoir in Extra-high Watercut Stage [D]. China University of Petroleum (East China), 2013.
[6] Wen T, Thiele M R, Ciaurri D E, et al. Water-flood management using two-stage optimization with streamline simulation [J]. Computational Geosciences, 2014, 18(3-4):483-504.
[7] Zhang Xiangji. The Research of Well-net Array and the Optimization of Injection-production Parameters for Super-low Permeability Reservoir [D]. China University of Petroleum (East China), 2011.
[8] Reynolds A C, Liu X. Gradient-based Multi-objective Optimization with Applications to Waterflooding Optimization [J]. Computational Geosciences, 2016, 20(3):677-693.
[9] Zhao X, Jiang B, Qiang X U, et al. Well pattern design and optimal deployment for coalbed methane development [J]. Petroleum Exploration & Development, 2016, 43(1):89-96.
[10] Dong Jie. Water Injection Development Method for Development of Fine Water Drive [J]. Journal of Yangtze University (Natural Science Edition), 2016, 13(23):54-57+6-7
[11] Chen Cunliang, Wang Xiang, Liu Xue, et al. Isostatic Displacement of Waterflooding Multi-Layer Reservoir Based on Maximum Net Present Value [J]. Special Oil & Gas Reservoirs, 2019, 26(01):122-125.
[12] Qian Chen, Lili Zuo, Changchun Wu, et al. Supply adequacy assessment of the gas pipeline system based on the Latin hypercube sampling method under random demand [J]. Journal of Natural Gas Science and Engineering, 2019, 71.