Research on well pattern optimization for secondary development of new layer system in old oilfield

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Abstract. The Es3 reservoir of Jin45 fault block has been developed for many years, and now it is faced with problems such as high water content, serious casing damage. In order to change the current development status of Jin45 fault block, the Es2 reservoir is put into development which located in the upper part of Es3 reservoir. The well pattern direction, well pattern form and well pattern density of Es2 reservoir are optimized by various methods in this study. On the basis of Es2 reservoir well pattern optimization study, the new well pattern of Es2 reservoir and the old well pattern of Es3 reservoir are comprehensively considered and compatibly adjusted. While the new well pattern is put into development, the injection-production system of the old well pattern is improved by using the new drilling wells, and the potential remaining oil is exploited, which lays a foundation for the efficient development of the old oilfield.

1. Preface
The main oil-bearing formations of Jin45 fault block are Es2 and Es3 reservoir, among which Es3 reservoir was developed in 1984 with a triangular well pattern with well spacing of 300m. At present, Es3 reservoir has entered the late stage of development, with water content above 90% and casing-damage ratio above 80%. The Es3 reservoir development situation is very severe, of which injection-production system is incomplete and water flooding control degree is low. In order to change the current situation of reservoir development, the Es2 reservoir located in the upper part of Es3 member is put into development. The Es2 reservoir has a substantial reserve volume to be put into development with a set of layer system. Therefore, it is determined to carry out the integral secondary development of the new and old layer system in Jin45 fault block. The old well pattern of Es3 reservoir and the new well pattern of Es2 reservoir are taken into comprehensive consideration. And the compatible adjustments are taken into account to achieve the high-efficiency development of the old oilfield.

The structure of Es2 reservoir is a nose-like structure, the sedimentary facies is a delta front subfacies, and the oil-bearing layer is stable. The Es2 reservoir is located in the upper part of the Es3 reservoir, which has a good structural inheritance from the Es3 reservoir. The average thickness of oil layer drilled by single well is 14.5 m / 4.5 layer, the average porosity is 16.2%, and the permeability is 13.5md. It is a medium porosity and low permeability reservoir.
2. Optimization of well pattern direction
In the process of oilfield development, horizontal principal stress and sand body distribution direction can provide important reference for well pattern deployment. Generally, the fracture produced by fracturing extends along the direction of maximum horizontal principal stress, and the main flow line of injected water is the main stress direction or sand body distribution direction. Therefore, the water injection wells should not be deployed in the direction of maximum horizontal principal stress or sand body distribution during water flooding development. According to the sedimentary facies study of Es2 reservoir, the direction of sand body distribution is mainly northeast. At the same time, referring to the well pattern deployment experience of domestic low-permeability reservoirs [1-2], the well array direction of water injection wells should be parallel to the direction of maximum principal stress as much as possible to achieve better water flooding development results. Considering the principal stress direction and sand body distribution direction comprehensively, the water injection well array direction of Jin45 fault block is about 60° north by east.

3. Optimization of well pattern form
The optimization of well pattern in low permeability reservoir mainly considers the final recovery degree, anhydrous production period and well pattern adjustment flexibility. The reasonable well pattern form of Es2 reservoir in Jin45 fault block is optimized by numerical simulation method. According to the geological conditions of the reservoir, the stratified geological model of single sand body is established on the basis of the structural characteristics, the paleocurrent direction, the water injection effective direction and the fracture monitoring direction [3]. Then three well pattern forms of triangle, square and rhombus are designed for optimization.

![Figure 1. Residual oil saturation of different well pattern forms](image)

The residual oil saturation of different well pattern forms can be seen from the oil saturation distribution graph as shown in figure 1. The residual oil of rhombic well pattern is mainly distributed between water injection wells due to the large well spacing of water injection well array and the slow establishment of effective displacement pressure on water flooding system. The water drive of square well pattern is relatively uniform, and the residual oil is dispersed. The residual oil of triangle well pattern is mainly distributed between oil wells, and the residual oil distribution is relatively concentrated.

![Figure 2. Relation of water content and recovery degree in different schemes](image)
The relationship curve of water content and recovery degree of different schemes can be seen in figure 2. Under the same recovery degree in the initial stage of development, the water content of square well pattern with 280m well spacing and square well pattern with 300m well spacing is higher, while the water content of triangular well pattern with 300m well spacing and rhombic well pattern with 300m well spacing is lower. The water content of triangular well pattern with 300m well spacing is the lowest. As there are many old wells available in the well pattern of Es2, it is necessary to adjust the new well pattern of Es2 and the old well pattern of Es3, while the triangular well pattern has better consideration for the available old wells in Es2 well pattern, so the irregular triangular well pattern is determined for development.

4. Optimization of well pattern density
The reasonable well pattern density is directly related to the degree of water drive control, water drive recovery and oil recovery rate of reservoir. Generally speaking, the higher the well pattern density is, the higher the water drive recovery is. Under certain single well productivity condition, the denser the well pattern is, the higher the oil production rate is. However, on the other hand, well pattern density is one of the most important factors that determine the investment in oilfield construction. With the increase of well pattern density, the construction investment will increase greatly. Therefore, the selection of well pattern density is based on the comprehensive evaluation of economic benefits after balancing the above factors. In this study, the actuating pressure gradient method and economic intersection method are mainly used to demonstrate the reasonable well pattern density.

4.1. Actuating pressure gradient method
The empirical formula for determining the critical well spacing based on the reservoir physical and fluid properties of low permeability reservoir is as follows [4]:

$$D_{lim} = 3.226 \Delta p \left( \frac{k}{\mu} \right)^{0.5992}$$

In the formula: $D_{lim}$ — technical limiting radius, m; $\Delta p$ — producing pressure drop, Mpa; $\mu$ — the viscosity of fluid, mPa.s; $k$ — permeability of formation, um2.

When the producing pressure drop is calculated as 12~15Mpa, the critical well spacing is about 255~318m as shown in table 1.

| $\Delta p$ (MPa) | k (mD) | $\mu$ (MPa.s) | $D_{lim}$ (m) | well spacing (m) |
|-----------------|--------|---------------|--------------|-----------------|
| 12              | 13.5   | 1.85          | 99.4         | 254.7           |
| 15              | 13.5   | 1.85          | 124.2        | 318.4           |

4.2. Economic intersection method
Based on the consideration of geological factors, reservoir engineering theory and the introduction of economic input and output factors, the method of calculating economic optimal well pattern density and economic limiting well pattern density is derived [5-6].

The future value of crude oil sales revenue during the oilfield development period ($V_1$) is as follows:

$$V_1 = G [NE_D e^{-a/s} / t][1 + (1+i) + (1+i)^2 + \Lambda \Lambda + (1+i)^{-1}]$$

$$a = -S \cdot \ln \left( E_R / E_D \right)$$
In the formula: 
- $G$ — crude price, Yuan/t;
- $i$ — discount rate, f;  
- $N$ — OOIP, 10⁴t;
- $t$ — development life, a.

The future value of the development investment ($V_2$) is as follows:

$$ V_2 = ASM[1+i+(1+i)^2i + \Lambda \Lambda + (1+i)^{t-1}i] $$  

(4)

In the formula: 
- $A$ — oil-bearing area, km²;
- $M$ — total single well investment, Yuan.

The future value of the operating and administrative costs during the development period ($V_3$) is as follows:

$$ V_3 = P[NE_D e^{-a/s} / t][1+(1+i)+(1+i)^2 + \Lambda \Lambda + (1+i)^{t-1}] $$  

(5)

In the formula: 
- $p$ — operating cost per ton of oil, Yuan/t;

Then the future value of net income ($V$) is as follows:

$$ V_I - V_2 - V_3 = C[NE_D e^{-a/s} / t][(1+i)^{t-1}] - ASM(1+i)^{t-1} - P[NE_D e^{-a/s} / t][(1+i)^{t-1}] $$  

(6)

When $V=0$, $S$ is the limiting well pattern density $S_{limit}$.

Assume $y_1 = [NE_D e^{-a/s} / t](G - P)[(1+i)^{t-1}] / i$

$$ y_2 = ASM(1+i)^{t-1} $$  

(7)

(8)

The limiting well pattern density $S_{limit}$ can be found by economic intersection method when $y_1 = y_2$.

When $dV / dS = 0$, $S$ is the optimum well pattern density $S_{optimum}$, we can find:

$$ [aN(G-P)E_D / t] [(1+i)^{t-1} / i] e^{-a/s} = AM(1+i)^{t-1} S^2 $$  

(9)

Assume $y_3 = [aN(G-P)E_D / t] [(1+i)^{t-1} / i] e^{-a/s}$

$$ y_4 = AM(1+i)^{t-1} S^2 $$  

(10)

(11)

The optimum well pattern density $S_{optimum}$ can be found by economic intersection method when $y_3 = y_4$.

Figure 3. Economic limiting and optimum well pattern density of Jin45 fault block

The well pattern density calculated by economic intersection method is as shown in figure 1. When oil price is 60 dollars, the economic limiting and economic optimum well pattern density of Jin45
block are 24.2 well/km² and 12.6 well/km² respectively, and the economic limiting and optimum well spacing of triangle well pattern are calculated as 218m and 303m respectively.

5. **Compatible adjustments of new and old well pattern**

Jin45 fault block is the secondary development of old oilfield. The Es3 reservoir has entered the late stage of water flooding development. The well casing damage of Es3 reservoir has become serious, which cannot form integrated injection and production well pattern, but the residual oil potential is still large. In order to better exploit residual oil of Es3 reservoir and save investment of new drilling wells, the new well pattern of Es2 reservoir and the old well pattern of Es3 reservoir should be combined comprehensively and adjusted compatibly at the same time. The adjustment principles are mainly contain three points. Firstly, the new drilling wells in new Es2 well pattern should be used to replace the water injection wells of casing damage in old Es3 well pattern as far as possible. Secondly, the water injection wells of Es3 well pattern return to Es2 well pattern serve as oil production wells. The third is to update the unrecoverable wells in the Es3 well pattern. After the well position of the Es2 well pattern is adjusted, the updated well is shared with both Es2 and Es3 well pattern. Through the above adjustment principles, the injection production system of Es3 well pattern can be improved, the degree of water drive control can be increased, and the residual oil can be exploited to the maximum extent.

Based on the study of well pattern optimization in Es2 reservoir, the well pattern deployment is carried out according to the principle of comprehensive combine and compatible adjustment. The total number of new drilling wells is 31 after adjustment, including 4 wells shared by Es2 and Es3 well pattern. 27 old wells in Es3 well pattern are used to serve as oil production wells in Es2 well pattern. 8 new drilling wells in Es3 well pattern are used to serve as water injection wells. The total recover production capacity is 2.88×10⁴t. By combining the new and old well pattern and adjusting new and old wells, it not only makes full use of the old wells, reduces a large amount of drilling well investment, but also improves the degree of water drive control in Es3 reservoir, which lays a foundation for the efficient development of the old oilfield.

6. **Conclusion**

(1) The secondary development well pattern of new layer system in old oilfield is based on the optimization research of well pattern direction, well pattern form and well pattern density of Es2
reservoir. The new well pattern of Es2 reservoir and old well pattern of Es3 reservoir are comprehensively considered and compatibly adjusted to form a set of independent triangular development well pattern with well spacing of 300m.

(2) The principle of well pattern adjustment for new and old layer systems is determined as follows. Firstly, the water injection wells of casing damage are replaced by new drilling wells in the old well pattern. Secondly, the water injection wells of old well pattern return to the new well pattern serve as oil production wells. Thirdly, in view of some wells cannot be repaired in old well pattern, the renewed wells are shared by both new and old well pattern. Through the above adjustment principles, it not only makes full use of the old well, reduces a large amount of drilling investment, but also improves the water drive control degree of the old well pattern, which lays a foundation for the achievement of high-efficiency development of reservoir. And this study has valuable reference significance for the development of other similar reservoirs.

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