Optimization of horizontal well pattern in low permeability layered reservoir

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Abstract. The southern part of Jin45 fault block is a low permeability layered reservoir with thin oil layer thickness. And the development of horizontal well pattern has good economic benefit in Jin45 fault block. The oil layer distribution of reservoir is quite different. The distribution of main layer is stable, but the distribution of non-main layer is unstable. In this study, through reservoir engineering method and numerical simulation method, the horizontal well pattern direction, well pattern form, well spacing and horizontal well length are optimized to determine the horizontal well pattern of main layer. On this basis, according to the principle of “parallel deployment of horizontal wells and sharing injection-production well pattern”, the horizontal well pattern of non-main layer is preliminarily designed to ensure the development effect and economic benefit to the greatest extent.

1. Introduction
The southern part of Jin45 fault block is a low permeability layered reservoir with thin oil layer thickness and good economic benefit of horizontal well pattern development. Vertically, there are many sets of oil layer, which are divided into four sand groups with an average oil layer thickness of 14.5m. Among the four sand groups, sand formation (IV) is the main layer with stable oil layer distribution. The average oil layer thickness drilled by single well is 5.6m, the average porosity is 16.2%, and the average permeability is 13.5md. Jin45 fault block is a low-to-moderate porosity and low permeability reservoir.

The sand body of main layer in the southern part of Jin45 fault block is nearly east-west trending. At present, the production interval of oil wells that has been put into production is the oil layer of sand formation (IV). The oil well has high production capacity, with average single well daily oil production of 7.8t in the initial stage. The oil layer distribution in sand formations of (I), (II) and (III) is unstable, and the production capacity of oil well needs to be confirmed. In order to achieve the efficient and stable development of reservoir, the horizontal well pattern optimization of the main layer sand formation (IV) in the southern part of Jin45 fault block is studied, then the horizontal well pattern design of the non-main layer is carried out on the basis of the horizontal well pattern optimization in the main layer.
2. Optimization of horizontal well pattern in main layer

2.1. The direction of horizontal well pattern

In the process of oilfield development, horizontal principal stress, fracture direction and sand body distribution direction can provide reference for the research of well pattern direction. Generally, the fractures generated by hydraulic fracturing are extended along the direction of maximum horizontal principal stress or sand body distribution in the crust. Meanwhile, the natural fractures are also easily generated along the direction of maximum horizontal principal stress [1-2]. Therefore, the direction of horizontal well should be perpendicular to the direction of principal stress. The water injection well should not be deployed in the direction of horizontal well maximum horizontal principal stress and sand body distribution.

Because of the poor physical property of reservoir, the oil wells need to be fractured before put into production. It is necessary to study the fracture direction, when the well pattern direction is to be determined. According to the artificial fracturing monitoring data and sedimentary microfacies research result, the sand body distribution direction of the main layer is nearly east-west, the sand body distribution direction of the eastern well area is northeast, and the sand body distribution direction is basically consistent with the fracture direction. Therefore, in the design of horizontal well pattern, the southern well area adopts nearly north-south direction horizontal well pattern deployment, while the horizontal well direction of eastern well area is north by west. The direction of well pattern deployment is perpendicular to the sand body distribution direction and fracture direction.

2.2. The form of horizontal well pattern

At present, horizontal well pattern mainly includes “horizontal well injection + horizontal well production” and “vertical well injection + horizontal well production”. There are many old wells can be used in Jin45 fault block, and the oil layer distribution of non-main reservoir is unstable. In order to make full use of old wells, the “vertical well injection + horizontal well production” well pattern is determined. And new vertical wells are drilled to make further understand of the development status and production capacity in non-main layer reservoir. Through numerical simulation method, the well pattern of “vertical well injection + horizontal well production” is further studied.

In the well pattern design of “vertical well injection + horizontal well production”, four kinds of injection-production well pattern are mainly selected and optimized, including the seven-point method (scheme 1), five-point method (scheme 2), waist staggered type (scheme 3) and waist determinant type (scheme 4).

![Figure 1. Schematic diagram of four injection-production pattern schemes](image-url)
According to the numerical simulation result, scheme 1 (seven-point injection-production well pattern) and scheme 3 (waist staggered injection-production well pattern) have relatively uniform waterline advance, good development effect and high recovery degree. The scheme 2 (five-point injection-production well pattern) has small water flooding swept volume, low water flooding rate in the middle reservoir of horizontal well and the worst water flooding effect.

Figure 2. Numerical simulation results of waterline advance

In terms of the recovery degree (Fig. 3), the seven-point method of injection-production well pattern has the best development effect with the highest recovery degree at the same water content, while the waist injection-production well pattern has the worst development effect.

Figure 3. Relation curve between water content and recovery degree

The seven-point injection-production well pattern is adopted in this deployment. In order to improve the oil recovery rate of reservoir and extend the water free production period of horizontal well, the waist wells are used to produce oil in the initial stage. Then the waist wells are transformed to be injection wells in the later stage.
2.3. The spacing of horizontal well pattern

Horizontal well pattern spacing is related to starting pressure gradient, injection-production pressure difference, reservoir effective thickness, horizontal well length, fracture and other factors. The horizontal well pattern spacing formula \([3-4]\) in low permeability reservoir is as follows.

\[
P_e - P_w > \left( \frac{R_w}{2} - \frac{L}{2} \right) \ln \frac{2R_w}{L} + \left( \frac{h}{2r_w} - r_w \right) \frac{h}{2L} \ln \frac{h}{2\pi r_w} G
\]

In the formula:
- \(G\) — starting pressure gradient, Mpa/m;
- \(P_e\) — initial reservoir pressure, Mpa;
- \(P_w\) — bottom hole flowing pressure, Mpa;
- \(h\) — reservoir effective thickness, m;
- \(L\) — horizontal well length, m;
- \(R_w\) — wellbore radius, m;

If the injection-production pressure difference \((P_e - P_w)\), starting pressure gradient \((G)\), reservoir effective thickness \((h)\), horizontal well length \((L)\) and wellbore radius \((R_w)\) are given, the technical critical well spacing can be determined by iterative computation. According to the formula, under the condition of given horizontal well length and injection production pressure difference, the critical well spacing decreases with the increase of starting pressure gradient, and the critical well spacing increases with the increase of horizontal well length and injection production pressure difference (Fig. 4 and 5).

![Figure 4. Relation curve of critical well spacing with different horizontal well length](image)

![Figure 5. Relation curve of critical well spacing with injection-production pressure difference](image)
According to the formula, when the injection-production pressure difference is 10–15 MPa, the critical well spacing is 350–410 m in the condition of horizontal well length is 500 m (Tab. 1). According to the calculation result of horizontal well spacing, considering that horizontal wells are fractured and put into production by dumbbell type fracture arrangement, the designed fracture half-length is about 80–120 m, and the horizontal well spacing is determined to be about 500 m.

Table 1. Calculation parameters of critical horizontal well spacing

| $\Delta p$ (MPa) | $h$ (m) | $L$ (m) | $R_w$ (m) | $G$ (MPa/m) | well spacing (m) |
|-----------------|--------|--------|----------|------------|-----------------|
| 15              | 5.8    | 500    | 0.1      | 0.044      | 410             |
| 10              | 5.8    | 500    | 0.1      | 0.044      | 350             |

2.4. The length of horizontal well

The increase of horizontal well length can improve the oil production capacity, but considering the frictional resistance and pressure loss of fluid in the horizontal well bore, the oil production increase extent of horizontal well is smaller and smaller with the increase of horizontal well length. When the horizontal well is long, the pressure drop is very small at the end of horizontal wellbore. At the same time, the increase of horizontal well length raises the investment cost of horizontal well [5], and the geological complexity and risk are also increasing. So there is an optimal length of horizontal well.

According to the prediction result of single well investment and production [6-7], the relationship curve between internal rate of return and horizontal well length under variable oil price can be obtained by using the general economic evaluation method of new oilfield development program. From the curve of internal return rate, when the horizontal well length is less than 700 m, the internal return rate raises with the increase of horizontal well length. However, the increase amplitude of internal return rate decreases after 500 m of horizontal well length, and the internal return rate gradually decreases after 700 m of horizontal well length. Therefore, the length of horizontal well is determined to be about 500-700 m (Fig. 6).

Figure 6. Relation curve of horizontal well length with internal rate of return

3. Design of horizontal well pattern in non-main layer

Due to the unstable non-main layer distribution of (I), (II) and (III) sand formation and the production capacity of oil well is uncertain, urgent development of horizontal well pattern will cause economic losses. The main layer of the Jin45 fault block is located in the lower part of the reservoir, and the non-main layer is located in the upper part of the reservoir. Therefore, the reservoir can be developed with
two or three layers of horizontal well pattern after the production capacity of non-main layer oil wells is realized. The design principle of well pattern deployment is as follows. Firstly, horizontal well pattern of non-main layer should be deployed in parallel with horizontal well pattern of main layer as far as possible, and multiple sets of horizontal well pattern should share one set of water injection system. Secondly, the horizontal well length in different layers should be adjusted according to the distribution of oil layer. Thirdly, the well test and production test of vertical wells around horizontal wells should be realized. The horizontal well drilling is carried out in the oil layer, when the production capacity of oil well is greater than critical production condition. In this way, the development of horizontal well pattern can achieve better economic benefit.

4. Deployment and implementation of horizontal well pattern

According to the optimization result of horizontal well pattern in the main layer, it is determined that the horizontal well pattern in sand formation (Ⅳ) is mainly composed of seven point well pattern and dumbbell shaped fracture making. Considering the distribution of surrounding old wells and oil layers, a total of 4 horizontal wells are deployed (Fig. 7). The spacing of horizontal well pattern is 500m, and the length of horizontal well is about 500m~700m.

![Figure 7. Horizontal well pattern deployment of main formation](image)

According to the deployment of horizontal well pattern in sand formation (Ⅳ) and the principle of well pattern deployment, the horizontal well pattern deployment design is carried out for sand formation (Ⅰ) and (Ⅲ) with relatively stable oil layer distribution (Fig. 8). A total of 8 horizontal wells are preliminarily deployed in sand formation (Ⅰ) and (Ⅲ).

![Figure 8. Horizontal well pattern deployment of non-main formation](image)

At present, the horizontal well pattern of sand formation (Ⅳ) has been implemented. A total of 4 horizontal wells have been drilled. The fracturing of oil wells in sand formation (Ⅳ) has been completed and will be put into production soon. And one horizontal well has been drilled in sand formation (Ⅲ). The implementation effect of horizontal well pattern is good.
5. Conclusion

(1) For low-permeability layered reservoir, the horizontal well pattern is deployed for the main layer with stable oil layer distribution and high oil production capacity firstly. Secondly, according to the principle of “parallel deployment of horizontal wells and sharing injection-production well pattern”, the horizontal well pattern of non-main layer is preliminarily designed. With the addition of non-main layer data, the horizontal well pattern will be implemented after the oil production capacity and oil layer distribution of non-main layer are confirmed. In this way, the development effect and economic benefit of reservoir are guaranteed to the greatest extent.

(2) For the horizontal well pattern development, the well pattern direction should be determined according to the geological characteristics of the reservoir firstly. Then the well pattern form, well pattern spacing and horizontal well length are studied through reservoir engineering method and numerical simulation method. Finally seven-point injection-production well pattern is adopted in sand formation (IV). The horizontal well length is about 500–700m, and the horizontal well spacing is about 500m.

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