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Well pattern optimization in a low permeability sandstone reservoir: a case study from Erlian Basin in China

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Abstract. Study on optimization of development well patterns is the core content of oilfield development and is a prerequisite for rational and effective development of oilfield. The study on well pattern optimization mainly includes types of well patterns and density of well patterns. This paper takes the Aer-3 fault block as an example. Firstly, models were built for diamond-shaped inverted 9-spot patterns, rectangular 5-spot patterns, square inverted 9-spot patterns and inverted 7-spot patterns under the same well pattern density to correlate the effect of different well patterns on development; secondly, comprehensive analysis was conducted to well pattern density in terms of economy and technology using such methods as oil reservoir engineering, numerical simulation, economic limits and economic rationality. Finally, the development mode of vertical well + horizontal well was presented according to the characteristics of oil reservoirs in some well blocks, which has realized efficient development of this fault block.

1. Background

Aer-3 fault block is located in the mid-north section of Aer sag anticlinal structure in Erlian Basin. The Aer-3 anticline is of complete structure shape, and its main part is divided into Aer-3 and Aer-3-1 well blocks by a NE Aer-3-1 fault leading to the east. The Aer-3 well block is on the downthrown side of this fault with development of faults; the oil zones are in long strips and the main oil-bearing reservoir is $K_1bt^{1\ down}$III2 oil formation.

The main type of sedimentation of Aer sag is fan delta. The lithology of reservoir rock is sandy conglomerate and pebbly sandstone with different size of grains. Its average porosity is 11.2% and its average permeability is 31.6mD. So it is low-porosity and low-permeability reservoir. The oil layers are stably distributed laterally and are well communicated; vertically, they are found in 30-220m well intervals. In average, the Class I oil reservoir drilled in a single well is 31.9m.

2. Determination of well array direction

Natural fissures are found in low–permeability reservoirs. These reservoirs have poor physical properties and large seepage resistance, so their natural productivity is very low, and the oil wells have to be fractured to have industrial oil streams. Fractures show double features in the development of oil field: on one hand, the presence of fractures improves the seepage ability of fluids; on the other hand, fractures are adverse to water injection. Hence, the right utilization of fractures can not only improve production of single wells, but also improve displacement sweep coefficient and recovery rate and it is the key to the placement of well patterns for development of low-permeability oilfields [1,2].

In the development of oilfield, the study on formation horizontal principal stress can provide reference for reservoir fracturing and well pattern placement. The commonly-used fractures created by hydraulic fracturing are generated and propagated along the maximum horizontal principal stress direction in the current crust, but also, natural fractures may occur along the maximum horizontal principal stress direction, so when an oilfield is developed by water injection, the water injectors should not be placed in the maximum horizontal principal stress azimuth of oil wells.

Dip log data has been obtained from 17 wells in Aer Oilfield. The maximum principal stress directions of the wells are almost the same, and the maximum horizontal principal stress azimuth is 240-270o. From the data of fracture monitoring, the fracture azimuth is about 42o north by east. The well pattern placement took into full account the effect of natural fractures and hydraulic fractures on well patterns. With reference to domestic well pattern placement for low permeability reservoirs [3], the direction of water injector array should be parallel as much as possible to the maximum horizontal principal stress direction in order to realize effective water flooding. Considering both the direction of maximum horizontal principal stress and the direction of hydraulic fractures, it is determined that the direction of water injector array for this block is about 60o north by east.

3. Determination of well pattern types

The optimization of well patterns for low permeability reservoirs shall be finally determined by the recovery percentage of reserves, economic benefits and flexibility in well pattern adjustment. In order to determine the reasonable well pattern type for low permeability reservoirs, models have been built for diamond inverted 9-spot pattern, rectangular 5-spot pattern, square inverted 9-spot and inverted 7-spot patterns under the same well pattern density. The penetration ratio of oil well fractures is 0.28; the non-linear seepage parameter is a=1, b=10; other parameters shall be according to actual situations [4,5].

Table 1. Technical indicator for different types of well patterns.

Indicator		Inverted 7-spot pattern	Diamond inverted 9-spot pattern	Square inverted 9-spot pattern	Rectangular 5-spot pattern
10th year	Recovery percentage	9.88	10.03	9.09	10.32
	Water content	10.95	31.59	41.54	36.25
20th year	Recovery percentage	17.13	15.45	14.69	15.91
	Water content	52.86	69.51	71.70	66.73

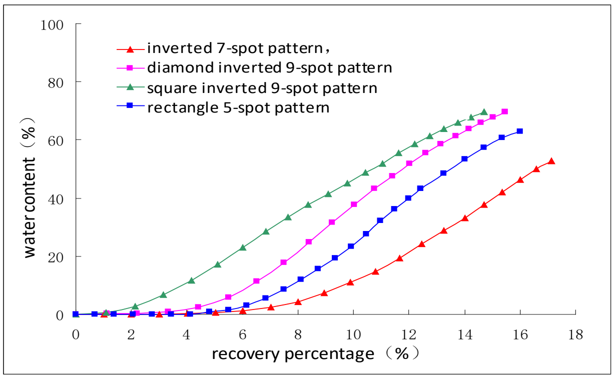

Figure 1. Diagram of correlation of water content and recovery percentage.

The result of numerical simulation (Table 1) shows that, in 20 years of development, the recovery percentage by inverted 7-spot pattern is the highest with the lowest water content, while the recovery percentage by square inverted 9-spot pattern is the lowest with highest water content. The diagram of correlation of water content and recovery percentage (Figure 1) shows that, at the same recovery percentage, the water content from inverted 7-spot pattern is the lowest, and the water content increases at a slow rate, so it is a more favorable well pattern type.

From the distribution graph of oil saturation (Figures. 2-5), it can be seen that , due to enlargement of well spacing of water injector array and while not considering the plane anisotropy of permeability, the diamond-shaped inverted 9-spot pattern has delayed the rate at which effective displacement pressure system is established on water injector line. So in the same development durations, the remaining oil is mainly found in water injector arrays. The remaining oil in inverted 7-spot pattern is mainly found in between the oil wells. The remaining oil saturation is relatively centrally distributed.

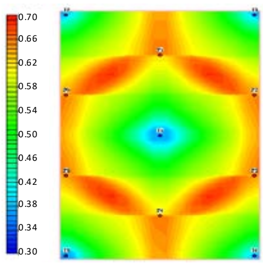

Figure 2. Saturation distribution of inverted 7-spot pattern.

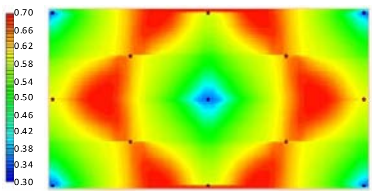

Figure 3. Saturation distribution of diamond inverted 9-spot pattern.

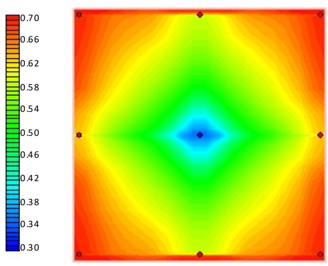

Figure 4. Saturation distribution of square inverted 9-spot pattern.

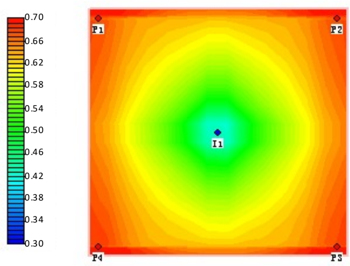

Figure 5. Saturation distribution of rectangle 5-spot pattern.

The distribution graphs of pressure gradient (Figures 6-9) show that the wells at the edge of square inverted 9-spot well pattern are favorably utilized, but pressure gradient field is not satisfactorily established near the wells at the corners, resulting in accumulation of remaining oil near the corner wells after 20-year development. Effective drive pressure system is not built in diamond-shaped inverted 9-spot well patterns, but effective drive pressure system is completely built in inverted 7-spot well pattern and rectangular well pattern. According to the forecasting result of recovery percentage, water content and effective pressure system from numerical simulation and also considering the development of faults in this block, it is determined that the triangle inverted 7-spot pattern be used to develop this block because the inverted 7-spot pattern has a better adaptability, so suitable for oil reservoirs with development of faults and distribution of long strip of oil layers.

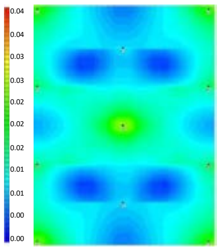

Figure 6. Pressure gradient distribution of inverted 7-spot pattern.

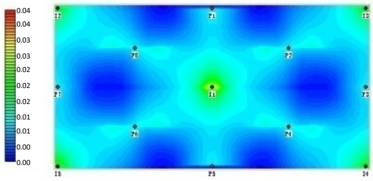

Figure 7. Pressure gradient distribution of diamond inverted 9-spot pattern.

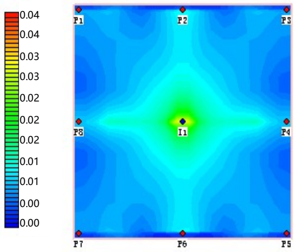

Figure 8. Pressure gradient distribution of square inverted 9-spot pattern.

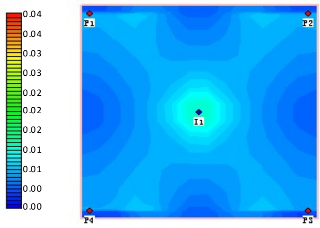

Figure 9. Pressure gradient distribution of rectangle 5-spot pattern.

4. Determination of well pattern density

Proper well pattern density is directly related to the degree of water flooding control by well pattern, the recovery rate by water flooding and oil production rate. Generally, the greater the well pattern density is, the higher the recovery rate by water flooding is. Meanwhile, under certain productivity of single well, the denser the well pattern is, the higher the oil production rate is. However, from another point of view, well pattern density is one of the most important factors in determining investment in oilfield construction. With the increase of well pattern density, the investment shall increase significantly; hence the option of well pattern density is determined by comprehensively considering and balancing all the above factors.

4.1. Empirical formula method

USSR scholar B. H. шелкачев, after conducting various studies, put forward the relation between well pattern density and oilfield recovery rate under water flooding:

$$E_R = E_D \exp(-aS) \tag{1}$$

According to actual situations of Huabei Oilfield and the derivation of B. H. шелкачев's formula[1] , we can arrive at the quantification formula for reservoir properties and crude viscosity with well pattern density. The relation is as below:

$$n = -\frac{0.8473}{\ln(Ev)}(\frac{k}{\mu_o})^{-0.2531} \tag{2}$$

Where, E_R—final recovery rate, decimal; E_D—oil displacement efficiency, decimal; *a*—well pattern index, decimal; *s*—well pattern density, ha/km^2; *n*—well pattern density, well/km^2; *Ev*—volumetric sweep factor, decimal; *K*—effective permeability, μm^2; μ_o—formation oil viscosity, mPa·s. Regardless of oil reservoir connectivity, the well pattern density mainly depends on reservoir permeability and crude viscosity among various reservoirs. Hence, this method is only applicable to reservoirs which have higher connectivity and high water flooding control degree. See Table 2 for calculations of reservoir physical properties and crude properties.

Table 2. Calculations of well pattern density for Aer-3 fault block.

Position	Permeability mD	Crude viscosity mPa·s	Volumetric sweep factor	Well pattern density well/km^2	well spacing m
K_1bt	31.6	2.0	0.85	18.0	258

4.2. Economic limits and economically-optimum well pattern density

The concept of ROI (return on investment) is introduced while fully considering the geologic factors. Based on B. H. шелкачев's formula, this paper has introduced the factors of economic input and output and derived the method to calculate the economically optimum well pattern density and economic limit pattern density.

The future value (V_1) of oil sales within the period of oilfield development is:

$$V_1 = G[NE_D e^{-a/s}/t][1+(1+i)+(1+i)^2+\cdots\cdots+(1+i)^{t-1}] = G[NE_D e^{-a/s}/t][(1+i)^t-1]/i] \tag{3}$$

Where, G—crude price, Yuan/t; i—discount rate, f; n—OOIP, 104t; t—development life, a.

$$a = -S\cdot\ln(E_R/E_D) \tag{4}$$

The future value (V2) of development investment is:

$$V_2 = ASM[1+i+(1+i)i+(1+i)^2 i+\cdots\cdots+(1+i)^{t-2}i] \quad = ASM(1+i)^{t-1} \tag{5}$$

Where: A—oil-bearing area, km2; M—total single well investment, Yuan.

The future value (V3) of operation and management expenditures during development life is:

$$V_3 = P[NE_D e^{-a/s}/t][1+(1+i)+(1+i)^2+\cdots\cdots+(1+i)^{t-1}] = P[NE_D e^{-a/s}/t][(1+i)^t-1]/i] \tag{6}$$

Where: p—operation cost per ton of oil, Yuan/t;

The future value (V) of net revenue is:

$$V1-V2-V3 = G[NE_D e^{-a/s}/t][(1+i)^t-1]/i] - ASM(1+i)^{t-1} - P[NE_D e^{-a/s}/t][(1+i)^t-1]/i] \tag{7}$$

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

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

$$y_2 = ASM(1+i)^{t-1} \tag{8}$$

The limit well pattern density S $_{limit}$ can be found by intersection method when $y_1 = y_2$.

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

$$[aN(G-P)E_D/t]\{[(1+t)^t-1]/i\}e^{-a/s} = AM(1+i)^{t-1}S^2 \tag{9}$$

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

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

The optimum well pattern density S $_{optimum}$ can be found by way of intersection when $y_3 = y_4$.

The well pattern density calculated by intersection method is as shown in Figure 10. When oil price is 2,582 Yuan, the economic limit and rational economic pattern density of Aer-3 block are 27.5well/km2 and 15.9well/km2 respectively; and the economic limit and economic well spacing are calculated as 205m and 269m respectively.

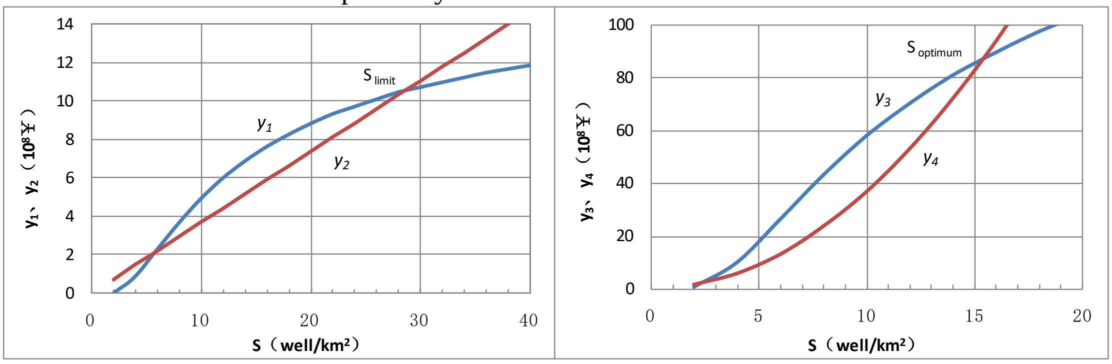

Figure 10. Economic limit and economic well pattern density of Aer-3 fault block.

y_1, y_2 (10^8 Yuan); S $_{limit}$

y_3, y_4 (10^8 Yuan); S $_{Optimum}$

4.3. Numerical simulation method

Five different programs were designed for injection-production well spacing: 150m, 200m, 225m, 250m and 300m. From the result of numerical simulation (Figure 11), it can be seen that, with the increase of well spacing, the recovery percentage becomes lower and the water content is also small at the end of the 20-year development. The curves of recovery percentage and water content (Figure 12) show that, when well spacing is less than 225m, the water content increases at a higher rate, i.e. a higher water content at the same recovery percentage; while when well spacing is greater than 225m, the rate of water content increase is relatively slow, i.e. a lower water content at the same recovery percentage. In comprehensive view of recovery percentage and the rate of water content increase, the 225m spacing is selected as the optimum well spacing for well blocks in Aer-3 fault block.

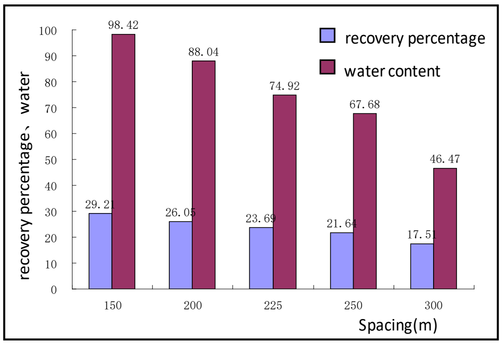

Figure 11. Histogram of water content and recovery percentage at the end of 20-year period of square inverted 9-spot pattern.

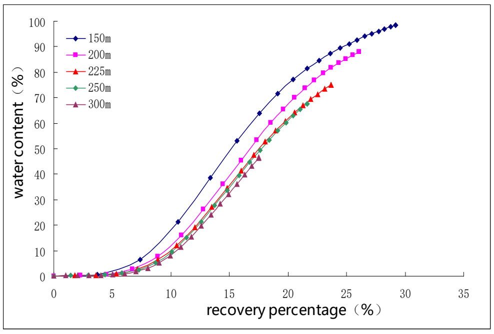

Figure 12. Relation curves of water content and recovery percentage.

The remaining oil distribution graph (Figure 13) shows that, with the increase of well spacing, the remaining oil saturation increases gradually and that the remaining oil is mainly found in the narrow strips between the oil producers. The pressure gradient distribution graph (Figure 14) shows that, with the increase of well spacing, the formation pressure gradient decreases gradually. The reservoirs with 225m well spacing have a relatively high recovery percentage and can fully establish an effective displacement pressure system.

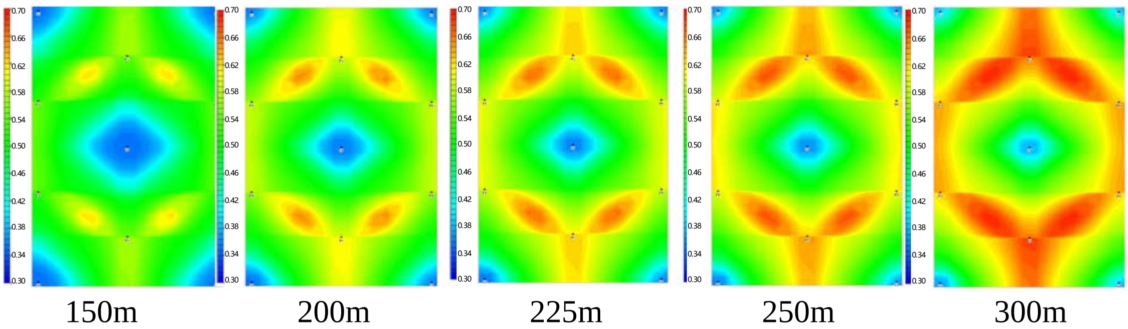

Figure 13. Saturation distribution of different well spacing in 20-year period.

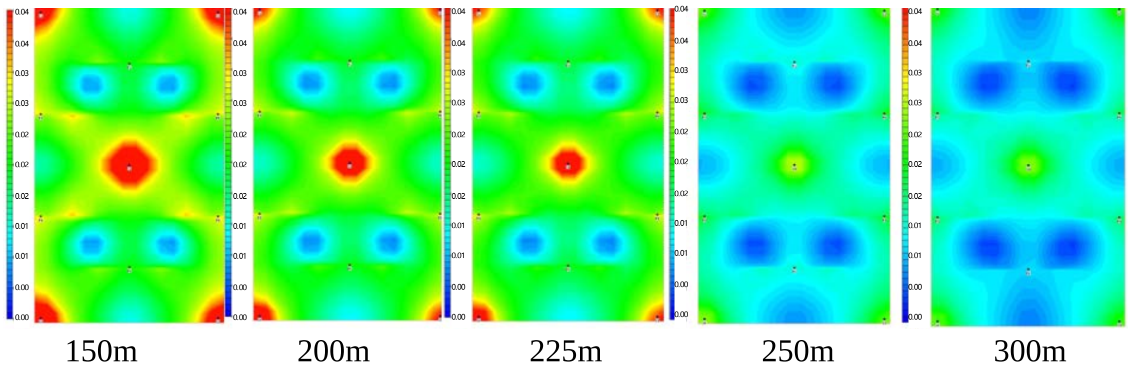

Figure 14. Pressure gradients distribution of different well spacing in 20-year period.

5. Horizontal well pattern

The oil reservoirs in the major well blocks of Aer-3 fault block have large thickness and a number of oil layers, and the reservoir types are mostly lithologic reservoirs with quick lateral variation. By reference to the layer series optimization of Ba-18 fault block of Baolang Oilfield and Baolige Oilfield and the experiences in separate strata development [6], a set of vertical well patterns were used for development in early stage to determine the distribution of oil layers; in later stage, horizontal wells were placed in areas where Nos. 1 and 2 single layer reservoirs have large thickness and are stably distributed in the major well blocks of Aer-3 fault block. The vertical wells were planned in combination with horizontal wells.

According to the contents of study on oil reservoir engineering, when there is friction in horizontal wells and the production is 80% of that with no friction [7], the length of horizontal section in horizontal well is the optimum length of horizontal section. According to calculation formula of optimum length of horizontal section in horizontal wells, the optimum length of horizontal section should be 330-480m [8,9] at different relative roughness. However, according to the target location of the horizontal well in Aer-3 well block, the target zone and the distribution of surrounding vertical wells, the possible length of horizontal section in horizontal wells is between 300 and 400m. The recommended length of horizontal section is about 350m.

6. Implementation effect

According to the types of well patterns and optimization of well pattern density, the Aer-3 fault block as a whole is to be developed using one set of series. The well blocks where oil reservoirs have developed in structural high are to be developed with two sets of series. The first set of well pattern is the basic pattern, using triangular pattern with well spacing of about 225m; the second set of well pattern is developed using vertical well plus horizontal well based on the vertical well patterns.

Altogether 29 oil producers have been put into operation in the main well block of Aer-3 fault block, including ten wells with two sets of well patterns: six horizontal wells and four vertical wells. Statistics shows that the water flooding control degree is 94.2%, and the producing degree by water flooding is 62.6%. So the water flooding development works well. The initial average oil production of single well was 10.7t/d (9.5t/d for vertical wells and 16.6t/d for horizontal wells). By the end of 2015, the accumulative oil production was 223,000 tons, which proved efficient development of the reservoirs.

7. Conclusions

(1) For low permeability reservoirs which need fracturing, the direction of water injector array should be parallel to the direction of maximum horizontal principle stress, so as to control directional water channeling to the most extent and extend the water-free production period. In view of the direction of the maximum principal horizontal stress and the direction of hydraulic fractures, it is determined that the direction of water injector array for this fault block is about 60^{o} north by east.

(2) In order to determine the proper well pattern types for this fault block, the models were built for diamond-shaped inverted 9-spot pattern, rectangular 5-spot pattern and square inverted 9-spot pattern under the same well pattern density. According to forecast result of the recovery percentage, water content and the effective pressure system at the end of the 20-year period and also considering the structural features of this fault block, it is determined that this block be developed using inverted 7-spot well pattern.

(3) Proper well pattern density is directly related to the water flooding control by well patterns, water flooding recovery rate, production rate and the economic benefits of oilfield development. This paper makes use of empirical formula, numerical simulation, economic limits and economic well pattern density determination method and determines that this fault block be developed using inverted 7-spot well pattern with 250m well spacing.

(4) Areas with large thickness of oil reservoir and subdivided development series of strata may be developed using vertical well plus horizontal well patterns based on the development with basic well

patterns, which can greatly increase oil production rate; meanwhile, making full use of the well with a set of basic well pattern for separate zone water injection can save investment and achieve good economic benefits from oil reservoir development.

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