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Optimization of Well Spacing Ratio of Injection Production Wells in Low Permeability Anisotropic Reservoir

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Abstract

According to the characteristics of anisotropy existed during the development of low permeability reservoirs, Shengli oilfield in Niu 20 reservoir as an example, by using reservoir numerical simulation method, considering the existing well pattern in low permeability reservoir, the effect of the well pattern, well spacing and array direction, and well pattern array distance ratio on the oilfield production capacity has been researched by numerical simulation. The results of the study show that: For the anisotropy of low permeability reservoirs, permeability ratio fixed, the semi logarithmic curve of well drainage distance ratio and degree of recovery shows a quadratic parabola relationship, the optimal well spacing ratio can be obtained by the curve fitting. And by numerical simulation of the actual reservoir, verify well array spacing ratio optimization to improve the degree of recovery.

Key words: Low permeability reservoir; Numerical simulation; Well pattern; Anisotropy; Water cut

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INTRODUCTION

During the development low permeability reservoir, the earlier water breakthrough would appear in the oil wells in the high permeability direction and the effectiveness and ultimate recovery of oilfield development would be on the decline, if the uniform well spacing was adopted on the low permeability reservoir with a presence of anisotropic permeability characteristics. Therefore, it is necessary to adjust the well pattern for this kind of characteristics of low permeability reservoir to improve sweep area and achieve good development results[1].

In order to investigate the development effect of low permeability anisotropy reservoirs, aiming circumstances reservoirs of natural fractures, using a array of wells and fracture direction was 0°, 22.5°, 45° angles, using the numerical simulation method well network type, well array spacing ratios on the extent of recovery were studied. According to reservoir simulation, we found that there is a second-degree parabola trend on the semi-logarithmic curve of the well array spacing ratio and the degree of recovery. By curve fitting formula, optimal well spacing ratio can be obtained under different permeability and different well pattern, and ultimately, the degree of recovery will be improved and the economic benefits of oilfield will be increased.

1. RESERVOIR PROFILEAND MODELING

The geology and fluid parameters in this article come from Shengli oilfield N20 block, a typical low permeability reservoir, which is well developed natural fractures well developed and strong pressure sensitivity. In this reservoir, the depth is 2,800-3,200 m, the average effective thickness is 10 m, the average porosity is 18.3%, and relative permeability curves is shown as Figure 1. After twenty years of development, the five-spot well pattern and artificial fracturing technology have been widely applied and improve the development of the oilfield.

A geologic model with 100 × 100 × 3 grids has been built up based on N20 reservoir geology, while the plane grid length is 10 m, vertical mesh length is 5 m, porosity is 0.2, the horizontal permeability is 10 × 10^{-3} μm^2, and vertical permeability is 5 × 10^{-3} μm^2. In addition, boundary conditions are the closed boundary conditions, and fixed liquid yield is applied in production wells. Specific formation and fluid parameters are listed in Table 1.

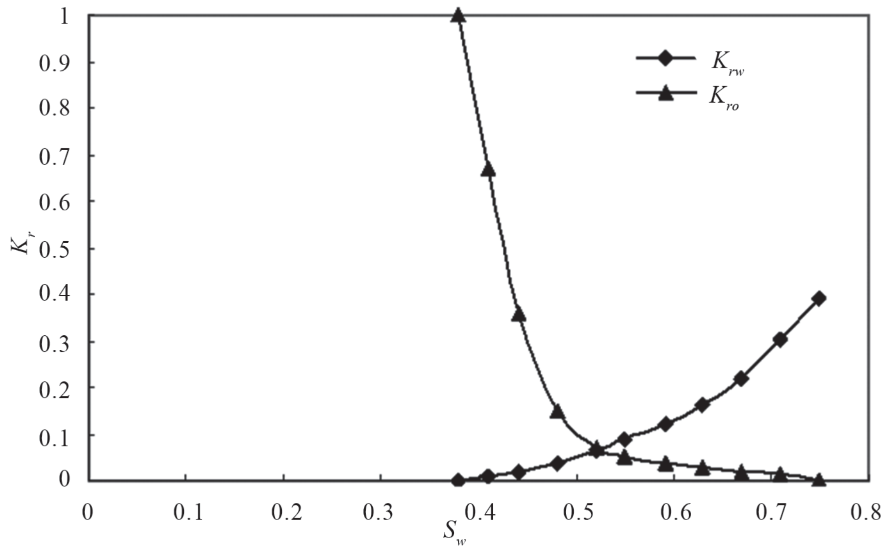

Figure 1
The Relative Permeability Curves

Table 1
Basic Parameters of the Model

Parameters	Value	Parameters	Value
Top of the reservoir depth (m)	3,000	Tank oil density (g/cm^3)	0.87
Original saturation pressure (MPa)	7.95	Formation water volume factor	1
Formation oil viscosity (mPa·s)	4.3	Formation water density (g/cm^3)	1.003
Rock compression coefficient (10^{-4}/MPa)	5	Formation water compression coefficient (10^{-4}/MPa)	5
Crude oil formation volume factor	1.13	Formation water viscosity (mPa·s)	0.25

2. DETERMINATION OF WELL PATTERN IN LOW PERMEABILITY RESERVOIRS WITH ANISOTROPIC PERMEABILITY

For isotropic reservoir, through literature investigation, the five-spot well pattern has been widely applied and has important effect on improved development effect, because of smaller interference between wells, more balanced each oil well being affected, and a larger sweep area.

In the exploration and development of low permeability reservoirs, due to the development of natural fractures and sedimentary environments, anisotropic reservoirs are prevalent in low permeability reservoirs[2]. The ordinary five-spot well pattern in low permeability anisotropic reservoir would cause water breakthrough on hypertonic direction, shortening of water-free oil production period and advancing initial water appearance of oil wells, for the different permeability in different directions. Therefore, it is necessary to study the effect of well patterns, well array direction, and well spacing ratio of injection production wells on oilfield recovery in low permeability anisotropic reservoirs[3].

2.1 Well Array Direction

According to many scholars[4,5], in low permeability anisotropic reservoir, the angle between the well array direction and reservoir fracture direction generally was 0°, 22.5°, and 45°[6]. We set the permeability in the horizontal direction of the geologic model as k_x = 50 × 10^{-3} μm^2, k_y = 10 × 10^{-3} μm^2, as five-spot well pattern was applied. Base on previous studies, the angle between the well array direction and reservoir fracture direction generally was set as 0°, 22.5°, and 45°, while the well spacing as 200 m. Otherwise, in this simulation, the production was fixed oilfield liquid yield, injection-production ratio remained 1:1. After 20 years of production, the recovery and water cut for different well array directions were shown in Figures 2 and 3.

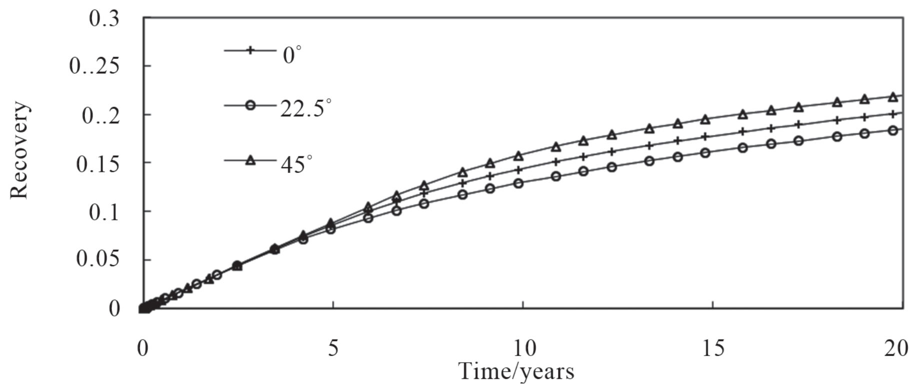

Figure 2
Plot of Recovery of Different Directions of Well Patterns

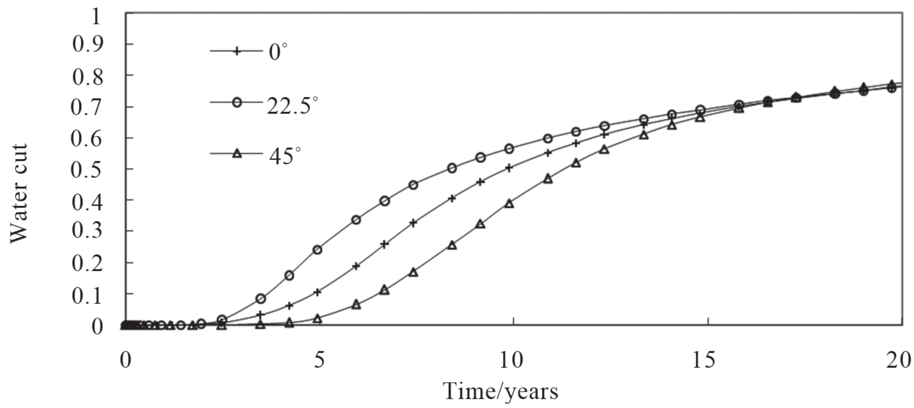

Figure 3
Plot of Water-Cut of Different Directions of Well Patterns

When the angle between the well array direction and reservoir fracture direction generally was 45°, the directions of wells and natural fractures direction ware parallel, making the highest level of recovery in unit time. This results indicate that, at this time, when the array direction was perpendicular to the maximum principal stress of the formation, the development effect had the optimum. The reason of this phenomenon due to delayed water breakthrough time and improved sweep efficiency.

In Figure 3, when connecting between production wells and injection wells was parallel to the direction of high permeability, it is likely to cause advancing initial water appearance, decreasing sweep efficiency, and lower recovery in unit time. However, in the angle of 45°, there is no production wells on the direction of high permeability, delaying water breakthrough time.

2.2 Well Pattern

According to the previous section, in low permeability anisotropic reservoirs, the highest level of recovery per unit of time would be obtained, when the ordinary five-spot well pattern array directions were parallel to the direction of fractures[7,8].

In fact, previous researches show that, in addition to the ordinary five-spot well pattern, rhombus inverted nine-spot well pattern and non-linear isometric well pattern had been adopted in low permeability reservoirs[9,10]. By turning injection wells intermittently on injection well arrays into the production wells, the ordinary five-spot well pattern would be transformed into rhombus inverted nine-spot well pattern. Moreover, by removing the production wells on injection well arrays, the pattern would be turned into non-linear isometric well pattern. And these two kind of patterns are shown in Figures 4 and 5, respectively.

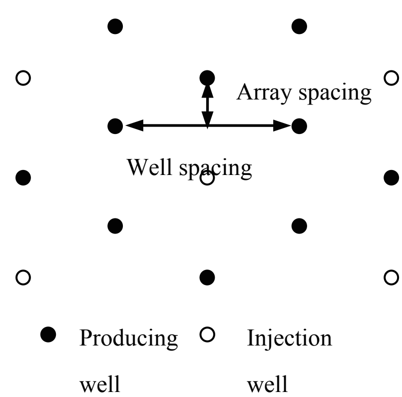

Figure 4
Inverted Nine-Spot Rhombus Well Pattern

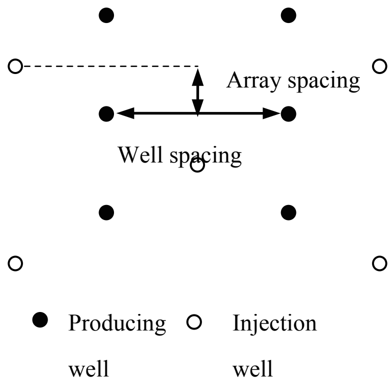

Figure 5
Non-Linear Isometric Well Pattern

2.3 Well Spacing Ratio

This section will discuss the optimal well spacing ratios of three different well patterns mentioned in prior part, and the effect of the permeability ratio on recovery.

As in earlier research, a geological model have been built up, while the permeability of x direction is k_x and y direction permeability is k_y. There are six case of low permeability anisotropic reservoir model in this section to simulate, and the data of the permeability are list in Table 2.

These well patterns maintained substantially the same density (maintained at around 25 / km^2 for impact of well pattern density is ignorable). Setting different array number indicates that five different well spacing and array spacing ratio of linear well pattern can be obtained, shown as Table 3.

Table 2
The Permeability of Experiment

Group number	k_x/mD	k_y/mD	k_x/k_y
1	10	10	1
2	20	10	2
3	30	10	3
4	40	10	4
5	50	10	5
6	100	10	10

Table 3
Table of Well Patterns of Different Injection-Production Well Spacing

Pattern	Well spacing/m	Array spacing/m	Well spacing ratio
Ⅰ	333	62	5.4
Ⅱ	400	100	4
Ⅲ	285	142.5	2
Ⅳ	200	200	1
Ⅴ	125	167	0.75

2.3.1 Five-Spot Well Pattern

For different well spacing ratios, numerical simulation obtained these recovery degrees in case of different permeability ratio at the end of 20 years.

The semi-logarithmic curve of recovery degree at the end of 20 years, with abscissa axis is different well spacing ratios, could fit well to parabolic law. And the optimal well spacing ratio, which corresponds the maximum recovery by the end of 20, could be obtained by curve fitting. In the case of reservoir with permeability ratio of 1, the semi-logarithmic curve of recovery and its regression equations are shown in Figure 6. Meanwhile, the results of the regression equations and corresponding optimal well spacing ratio of the six cases are list in Table 4.

Table 4
Optimal Well Spacing in Different Permeability Anisotropy

k_x/k_y	Regression equations	Optimal well spacing ratio
1	$y = -0.0288x^2 + 0.04x + 0.2152$	2.003
2	$y = -0.0285x^2 + 0.0409x + 0.2144$	2.049
3	$y = -0.0277x^2 + 0.0406x + 0.2137$	2.081
4	$y = -0.0274x^2 + 0.041x + 0.2134$	2.113
5	$y = -0.0267x^2 + 0.0408x + 0.213$	2.147
10	$y = -0.0239x^2 + 0.0388x + 0.2113$	2.252

According to the optimal well spacing ratio corresponding to different array spacing ratio, Figure 7 can be obtained, illustrating that well spacing ratio increases with increasing permeability ratio, but increased amplitude gradually becomes slow.

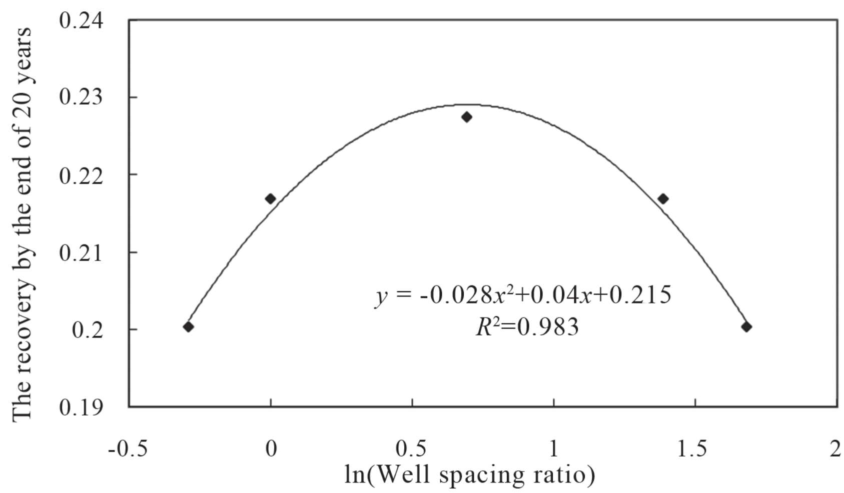

Figure 6
Plot of Recovery Degree at the End of 20 Years of Different Direction of Well Patterns in Permeability Isotropy

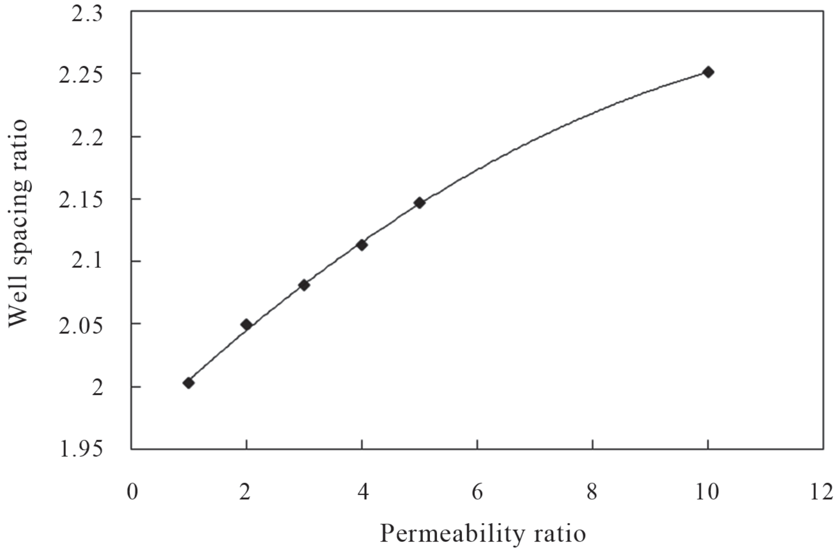

Figure 7
Plot of Optimal Well Spacing and Different Permeability Anisotropy

2.3.2 Rhombus Inverted Nine-Spot Well Pattern

Similar to the case of five-spot well pattern, the recovery degrees at the end of 20 years in case of different permeability ratio are calculated. By fitting the curves of recovery degree at the end of 20 years, the regression formula and corresponding well spacing ratios in case of different permeability ratios are shown in Table 5.

Table 5
Optimal Well Spacing in Different Permeability Anisotropy

k_x/k_y	Regression equations	Optimal well spacing ratio
1	$y = -0.0208x^2 + 0.0289x + 0.1977$	2.003
2	$y = -0.0174x^2 + 0.0261x + 0.196$	2.117
3	$y = -0.0167x^2 + 0.0263x + 0.1954$	2.198
4	$y = -0.0173x^2 + 0.0275x + 0.1953$	2.214
5	$y = -0.018x^2 + 0.0285x + 0.1953$	2.227
10	$y = -0.0196x^2 + 0.0302x + 0.1946$	2.241

Like the case of five-spot well pattern, according to the optimal well spacing ratio corresponding to different array spacing ratio, Figure 8 can be obtained, illustrating that well spacing ratio increases with increasing permeability ratio, but increased amplitude gradually becomes slow.

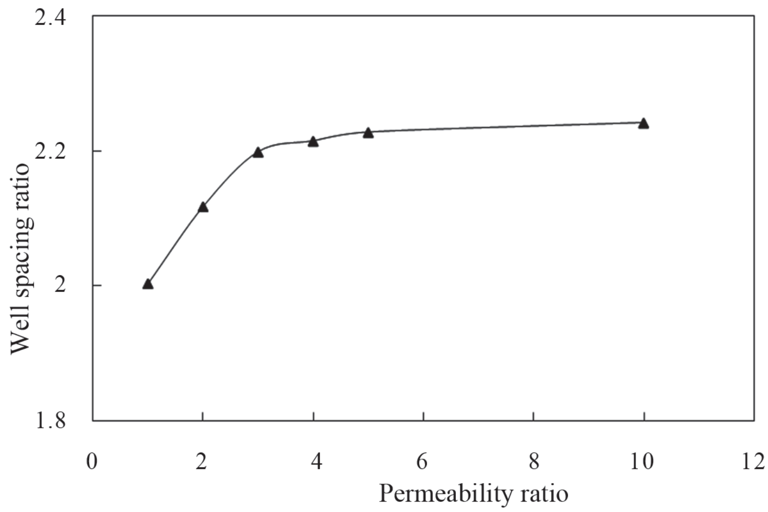

Figure 8
Plot of Optimal Well Spacing and Different Permeability Anisotropy

2.3.3 Non-Linear Isometric Well Pattern

Removing the corner wells in rhombus inverted nine-spot well pattern, the non-linear isometric well pattern with well density of 21 / km^2 is obtained. There are five well patterns with different well spacing ratios, through setting different arrays. Similar to other two kind of pattern, the regression formula and corresponding well spacing ratios in case of different permeability ratios are shown in Table 6. And the curve of optimal well spacing and different permeability anisotropy has a similar trend that well spacing ratio increases with increasing permeability ratio, but increased amplitude gradually becomes slow, shown as Figure 9.

Table 6
Optimal Well Spacing in Different Permeability Anisotropy

k_x/k_y	Regression equations	Optimal well spacing ratio
1	$y = -0.0019x^2 + 0.0087x + 0.1988$	1.115
2	$y = -0.0098x^2 + 0.0055x + 0.2011$	1.324
3	$y = -0.0197x^2 + 0.0154x + 0.2041$	1.478
4	$y = -0.0265x^2 + 0.0227x + 0.2062$	1.535
5	$y = -0.0313x^2 + 0.0281x + 0.2076$	1.567
10	$y = -0.042x^2 + 0.0415x + 0.2107$	1.639

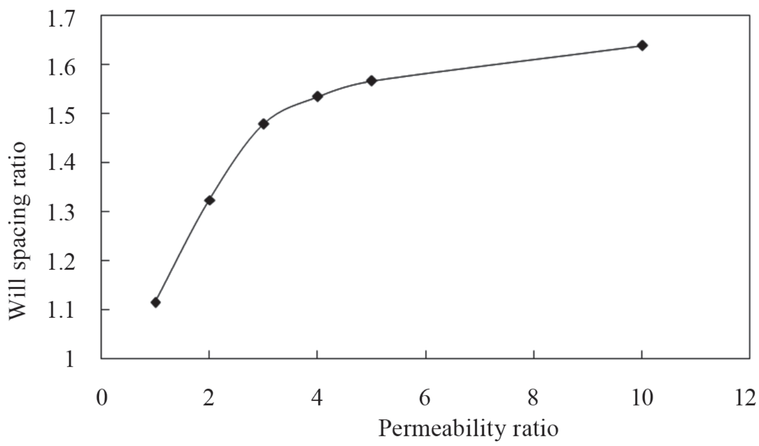

Figure 9
Plot of Optimal Well Spacing and Different Permeability Anisotropy

2.3.4 Results and Discussion

The simulation results of the three patterns in low permeability anisotropic reservoir are plotted in Figure 10, with dots, triangles, and crosses represent the patterns, respectively. As shown in the scatter gram, there is a phenomenon that the crosses are lower than other two kind of spots on vertical coordinate, resulting from a lower well density of non-linear isometric well pattern[11]. However, due to the uniform distribution of wells, five-spot well pattern has a greater degree of recovery in different low permeability anisotropic reservoirs.

For low permeability and anisotropic characteristics, in the three kinds of patterns, optimal spacing ratio increase with increasing permeability ratio. The production wells density around injection wells becomes larger, when the global well density increases. This trend may cause a too small array spacing and advance the water breakthrough. It is noteworthy that the crosses in Figure 10 are more disperse, means that the optimal spacing ratio in non-linear isometric well pattern is susceptible to permeability ratio, as a result of low injection well density. It is necessary a higher well spacing ratio to improve sweep efficiency, and then enhance recovery. When the permeability ratio of low permeability reservoirs exceed four, the increased amplitude of optimal spacing ratio gradually becomes slow, which is due to, in the high anisotropic reservoirs, water breakthrough will occur on the direction perpendicular to hypertonic direction, bringing down the degree of recovery.

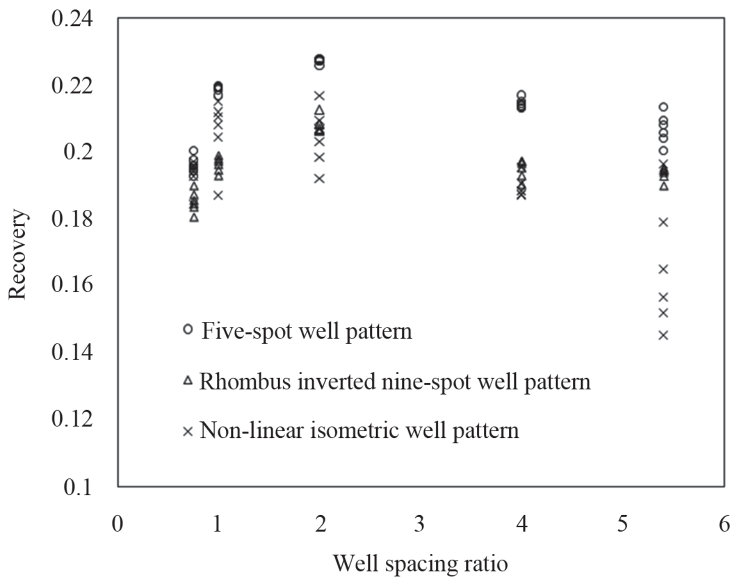

Figure 10
The Recovery of Different Well Pattern Under Different Well Spacing Ratio

CONCLUSION

(a) In the three patterns of this study, five-spot well pattern has the best recovery degree, meaning that it is optimal pattern for low permeability anisotropic reservoir. When connection direction between the production and injection wells was parallel to the direction of natural fractures, the degree of recovery per unit time was maximum, and the time of water breakthrough would be delayed.

(b) For anisotropic permeability reservoir, there is a second-degree parabola law on the semi-logarithmic curve of the well array spacing ratio and the degree of recovery, and optimal well spacing ratio under different permeability ratio can be obtained by curve fitting. The optimal well spacing ratio increases with increasing permeability ratio, but increased amplitude gradually becomes slow, when the permeability ratio exceeds 4.

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