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New Solution to Critical Injector-Producer Spacing Shaped Invert 9-Spot Area Well Pattern for Low-Permeability Reservoir

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Abstract

In view of the improper injector--producer spacing and low producing degree of low-permeability reservoir, according to water flooding characteristics of low-permeability with invert 9-spot well pattern, areal sweeping efficiency formula was adopted to calculate the areal sweeping efficiency for reservoir area; multiple linear regression was used to fit the mathematic model of areal sweeping efficiency, which was then used to work out the critical injector producer spacing under different injection-production pressure difference. Meanwhile, effective drainage factor was also used to calculate critical injector producer spacing, whose credibility of fitting data more than 95%. The computed results can be used to adjust the injector producer spacing of poor reservoirs and improve production efficiency of thin and poor reservoirs. Comparison of the data that include differential pressure, permeability, threshold pressure gradient, reasonable injection-production well pattern and space. etc from one block, in which injection pressure is high and difficult injection, which adjust well pattern and space can alleviate injection-production problem, and also estimation all the factors except water-sensitivity. etc.

Keywords*: Low permeability reservoir, critical injector producer spacing, invert 9-spot pattern, tight sandstone; Liaohe depression*

1. Introduction

According to various literature around the world, it generally would make the permeability upper limit as $50\times10^{-3}\mu m^{2}$. And from the development, we would make the low permeability oilfield as three kinds, that are low permeability oilfield, extra-low permeability oilfield and ultra-low permeability oilfield. To be specific, the low permeability oilfield has the characters which is oil reservoir is provided with certain nature productivity and industrial exploitation value without fracturing transformation, its permeability is $(10\text{-}50)\times10^{-3}\mu m^2$ .Extra-low permeability oilfield is provided with the low nature productivity in the oil reservoir, which would not have industrial exploitation value. It would develop economically and effectively unless it uses fracturing transformation. Its permeability is (1-10) $\times10^{-3}\mu m^2$. Ultra-low permeability oilfield has the character that although with fracturing transformation, its industrial exploitation capacity is not high, and it's hard to develop economically and effectively. The permeability is less than $1\times10^{-3}\mu m^2$.

Currently, solution to the critical injector-producer spacing on pattern water-flooding has been discussed on a world scale, which mainly take five-spot for example, but in the development practices of low permeability and ultra-low permeability reservoirs, which general adopted inverted 9-spot pattern in its initial stage. Since the injector-producer spacing ratio of inverted 9-spot pattern is 1:3; but the ratio of 5 spot well pattern is 1:1. Relatively speaking, it has more producing

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well, this is mainly because of economic considerations, recovery of low permeability reservoir is often lower, pressure conduction is also more difficult, and by way of converting some oil well to water injection can be used to turn inverted 9-spot pattern into 5 spot well pattern in its later stage of production, meanwhile, it also can reduce the injector-producer spacing and achieve good development effectiveness[1-5].

One block, Niuju in Liaohe Oilfield, its belongs to ultra-low permeability reservoir, the downdiptraps of anticline in Niuju section develops local small culmination of Sha II formation, which fault-noses formation titled westward, gentle slope of high part and steep downdiptraps. The type of reservoir rocks is clastic rocks and its mainly are glutenite, medium sandstone and siltstone come second which affected by nearby provenances and transported in a short distance, crude downdiptraps pores of reservoir rock. Its reservoir buried depth is 3060-3275m and has better oil property, which belongs to high quality thin oil. Its surface density of crude oil is 0.8205g/cm^3, the viscosity is 2.79mPa•S, the properties of formation water is sodium bicarbonate type ($NaHCO_3$). The average of its total salinity is 5112.42 mg/L, porosity is 9.5% and permeability is $2.6\times10^{-3}\mu m^2$. After adopting inverted 9-spot pattern well spacing and depletion development a year, and then begin water-flooding. As the growth of water injection time, it would gradually appear problems, which is high pressure in water injection wells, and hardly to achieve the regulated injection. So we could make a research on injection-production pattern, space and threshold pressure gradient by reservoir engineering methods except the water quality, and other factors like swelling clay minerals.

The areal sweep efficiency can quantitatively describe effective producing extent and mathematical model among areal sweep efficiency, injection-production pressure drawdown and injection-production well spacing, it also can research the relations among the quantitative description of areal sweep efficiency, injection-production pressure drawdown and injection-production well spacing. According to the definition of areal sweep efficiency, which can ensure the critical injector-producer spacing of effective development under the injection- production pressure in the thin and poor reservoir [6].

2. Areal Sweep Efficiency Fitting Formula Deduction

2.1. Determine the Start-Up Pressure Gradient

Amount of simulated experiments and field experiments indicated that the fluid would not conform to Darcy law when it porous flow at a low speed under the low permeability reservoir, and also has threshold pressure gradient. In fact, the fluid in the low permeability reservoir would have an additional resistance that is the adsorb resistance between oil and rocks except viscous resistance when it porous flow. Only when yield pressure overcome this additional resistance, the fluid could flow. This is threshold pressure phenomenon. So based this phenomenon, the scholars is widely believed that only when practical pressure gradient more than a certain critical value, the flow would occur, and this critical value called threshold pressure gradient.

We would apply capillary model method, so first we set a capillary which filled with a sort of fluid, and this fluid has a certain yield pressure value, it could flow under driving pressure. Then, the driving pressure acted on the fluid is $(P_1 - P_2)\pi r^2$, and the motion resistance of this fluid column is $2\pi rL(\tau + \tau_0)$. According to acting force balance principle, it can get

$$(P_1 - P_2)\pi r^2 = 2\pi r L(\tau + \tau_0) \quad (1)$$

In the equation $\tau = -\mu \frac{dv}{dr}$, after clearing out it, we can get

$$\frac{dv}{dr} = \frac{-\Delta p r}{2\pi r L} + \frac{\tau_0}{\mu} \quad (2)$$

In the equation, v represents flow velocity, m/s, ΔP represents pressure gradient Pa/cm; μ represents fluid viscosity, mPa•s; τ_0 represents the yield stress of the fluid, N; r represents capillary ratio, μm.

After solving the equation, we could get:

$$v = \frac{\Delta p}{4\mu L}(r_0^2 - r^2) - \frac{\tau_0}{\mu}(r_o - r) \quad (3)$$

The cell flow as follow:

$$dQ = v 2\pi r dr \quad (4)$$

After solving the equation, we could get:

$$Q = \frac{\pi r_0^4}{8\mu}\left[\frac{\Delta p}{L} - \frac{8\tau_0}{3r_0}\right] \quad (5)$$

The equation (5) is the flow formula which the fluid through capillary with yield value, the second item in brackets represents threshold pressure gradient. When the threshold pressure gradient more than this value, it would flow.

$$\frac{\Delta P}{L} = \frac{8\tau_0}{3r_0} \quad (6)$$

We could see that the threshold pressure gradient is inversely proportional to the capillary ratio, which also in direct proportion to the yield value. In the study of petrophysics properties, we could see that the relationship between capillary ratio and permeability is $r_0 = \sqrt{\frac{8K}{\phi}}$, take it to the equation (6), we could get

$$\frac{\Delta P}{L} = \frac{\sqrt{8\phi}\tau_0}{3\sqrt{K}} \quad (7)$$

Finally, we could get equation (8), and the threshold pressure gradient is inversely proportional to permeability squared.

$$\lambda = \frac{\Delta P}{L} = \frac{\sqrt{8\phi}\tau_0}{3\sqrt{K}} \quad (8)$$

In equation (8), λ represents threshold pressure gradient, MPa/m; ΔP represents differential pressure, MPa; L represents the length of the flow line, m; ϕ represents porosity, %; K represents the permeability, 10^{-3}μm^2; τ_0 represents the yield stress of the fluid, N.

From the point of view to analyze the rheological, when crude oil seepage in low permeability reservoirs, which exists a threshold pressure gradient, it represents some kind of ultimate shear stress when crude oil in the porous flow, it can get

Equation (9), inversely proportional to the square root of the start-up pressure gradient and permeability, with the ultimate shear stress is proportional to the τ_0.

$$\lambda = \frac{\Delta P}{L} = \frac{8}{9}\sqrt{\frac{\phi}{K}}\tau_0 \tag{9}$$

To analyze the threshold pressure gradient experiment data of the cored well (12 different well positions), and we would chose kerosene fluid and different permeability cores to carry on the threshold pressure gradient tests respectively. The kerosene viscosity is 2.77mPa•S, the density is 0.8149g/cm^3 and the experiment temperature is 70℃. The experiment results as follow:

Table 1. The Threshold Pressure Gradient Experiment Data of Different Permeability Cores in a Liaohe Oilfield Block

Rock No.	K ($10^{-3}\mu m^2$)	threshold pressure gradient($Mpa\cdot cm^{-1}$)	porosity (%)	μ (mPa·s)
X1	311.27	0.00183	22.89	2.38
X2	297.89	0.0024	22.71	2.38
X3	136.31	0.00231	17.46	2.38
X4	83.27	0.00261	16.07	2.38
X5	53.43	0.00356	14.47	2.38
X6	11.19	0.0051	18.84	2.38
X7	5.8	0.00686	17.13	2.38
X8	3	0.00771	13.6	2.38
X9	2.43	0.00866	11.74	2.38
X10	2.43	0.00939	8.15	2.38
X11	2.16	0.01027	13.31	2.38
X12	2.05	0.01086	10.02	2.38

From the Table 1, we could see that the smaller the permeability is, the bigger threshold pressure gradient value is, and when the permeability is less than the limit of $10\times10^{-3}\mu m^{2,}$ the change range of the threshold pressure gradient is the biggest. This block is ultra-low permeability oilfield, so when we calculate the critical spacing, we must consider the effect of threshold pressure gradient.

Draw threshold pressure gradient in Table 1 and the experiment data on the rectangular chart, we would get a relation curve as follow Figure 1:

According to the regression analysis, we could analyze the start-up pressure gradient of experimental data core wells, which can get the power function relations between threshold pressure gradient and permeability, can get the Equation (10) between the threshold pressure gradient and permeability. The correlation coefficient is

$$\lambda = 0.0131K^{-0.315} \tag{10}$$

According to the reservoir average permeability in this block, we could get the threshold pressure gradient is 0.091 MPa/m after calculating.

2.2. Areal Sweep Efficiency, Injection Pressure and Injection Production Well Spacing Formula Deduction

Non Darcy flow exit a threshold pressure gradient under a certain injection-production well spacing and pressure drawdown, which cannot be necessarily flowed in the area between the injection and production well. The areal sweep efficiency refers to the percentage injection agent affects area accounts for the pattern area. In invert nine-spot well pattern cell, the end and corner wells characters are completely different, which could make different basic calculate cells with water injection well respectively. As follow in Figure 2, so we should respectively study on invert nine-spot areal sweep regular of the end wells and corner wells.

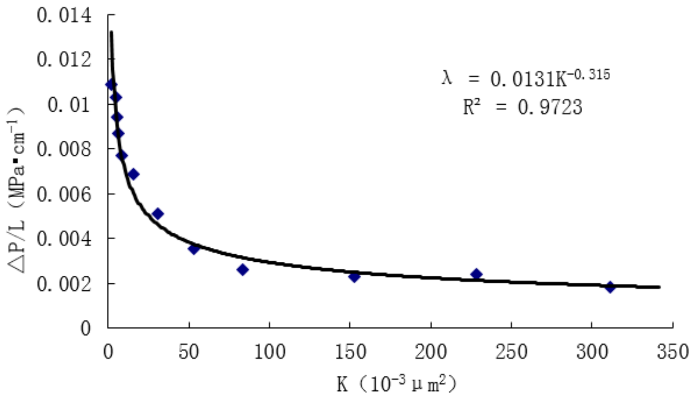

Figure 1. The Relation Curve between Threshold Pressure Gradient and Permeability

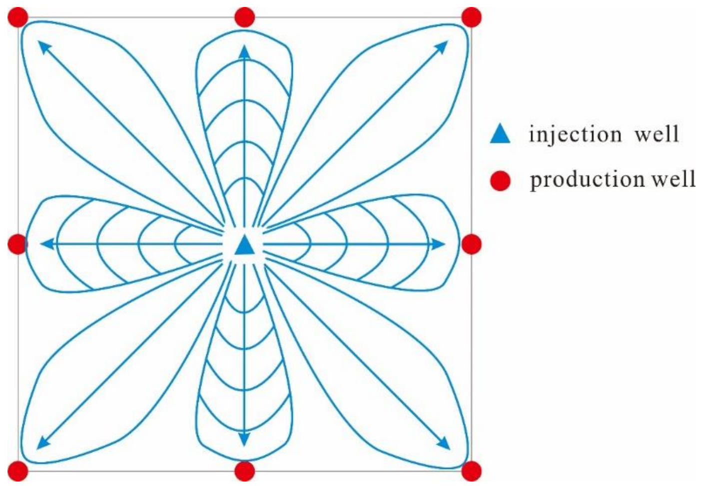

Figure 2. The Division Unit Chart of Invert 9–Sport Pattern

We would set a model, and suppose a single layer with homogeneity and uniform thickness, which injection well located ξ=0 and production well located ξ=1(ξis flow length). We should suppose that the different pressure between injection well and production well is constant, we should not consider the fluid flexible and the function among capillary force, gravity and water phase threshold pressure gradient but consider the effect of oil phase threshold pressure gradient. And then to get a flow pipe infinitesimal between injection well and production well, so according to low velocity non-Darcy basic formula and oil-water consistence equation, it would have an equation in cross section infinitesimal:

$$\int_0^{\xi} A(\xi)\,d\xi = \int_0^{t} \frac{\Delta q f'_w(S_w)}{\phi}\,dt \tag{11}$$

To calculate cell, we make the oil-water spacing as l and also flow pipe infinitesimal, so the injection well incremental angular is $\Delta\alpha_b$ and the production well incremental angular is $\Delta\beta_b$, as follow in Figure 3:

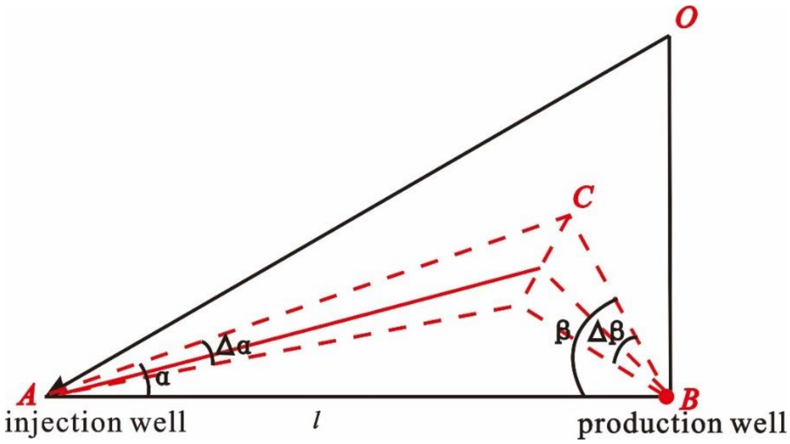

Figure 3. The Computation Unit Chart of Edge Well of Invert 9–Sport Pattern

The action angle of end well in the invert nine-spot well pattern is certain by $P_h - P_f - \lambda l \frac{\sin\alpha_0 + \sin\beta_0}{\sin(\alpha_0 + \beta_0)} = 0$, the max value is arctan0.5.

According to the stream tube model and the Beckley Leverett equation, we deducted 5 spot well pattern areal sweep efficiency calculation formula of Equation (12) [8] considering the starting pressure gradient, drawing the areal sweep coefficient as follows:

$$E_A = \frac{\frac{1}{2}\int_0^{\alpha_0} \frac{\frac{K}{\mu}\left[P_h - P_f - \lambda L \frac{\sin\alpha + \sin\beta}{\sin(\alpha+\beta)}\right]}{\frac{1}{2}\ln\frac{L\sin\beta}{r_w \sin(\alpha+\beta)} + \frac{\arctan 0.5}{\pi}\ln\frac{L\sin\alpha}{r_w\sin(\alpha+\beta)}} \cdot \frac{f_w'(S_{wf})t}{\phi} d\alpha}{\frac{L^2}{4}} \tag{12}$$

In Equation (12), α refers to Oil-water front at a position corresponding to the point of injection well, β refers to Oil-water front at a position corresponding to the point of view of production wells, α_0 refers to Inverted nine spot well pattern well start angle, with the maximum value arctan 0.5, P_h refers to Water injection well bottom hole pressure, MPa; P_f refers to Flowing bottom hole pressure in production wells, MPa; r_w refers to wellbore radius, m; $f_w'(S_{wf})$ refers to the change of water content rate; E_A refers to sweep efficiency, %.

According to the above formula, areal sweep efficiency of the block within different injection production well spacing and injection pressure can be calculated. But the formula is complex in practical computation and weak in actual operation. In order to avoid the complex computational process, the areal sweep efficiency model can be simplified by the use of the calculated data and multiple linear regression analysis. Injection production well spacing and injection pressure can be non-dimensionalized by using dimensionless ΔP, L and formula [9].

$$\Delta P_D = \left(Kh / 1.842\times10^{-3} q\mu B\right)\Delta P \tag{13}$$

$$L_D = L / r_w \tag{14}$$

In Equation (12), injection pressure $\Delta P = P_h - P_f$, ΔP_D is dimensionless pressure. In Equation (14), L_D is dimensionless distance. Use the multiple linear regression to fit dimensionless injection pressure, injection production well spacing and areal sweep efficiency, and establish a mathematical model for area sweep efficiency as follows:

$$E_A = a\Delta P_D + bL_D + c \tag{15}$$

2.3. Multiple Linear Regression

To calculate the data as the foundation data, using the least square method, multiple linear regression coefficient is as follows: a=0.972, b=-0.001, c=0.701.

Fitting 95% confidence interval for the regression coefficient matrix:

$$\begin{bmatrix} 0.6314 & 0.7323 \\ 0.9223 & 1.0362 \\ -0.0009 & -0.001 \end{bmatrix},$$

$R^2 = SSR/SST = 0.9633$. It represents that the area sweep efficiency values are 96.33%, and it may be determined by the regression model, the statistics are $F = (SSR/f_R)/(SSE/f_E) = 356.382$, the significance probability of variance analysis is $p \approx 0 < 0.05$, the degree of fitting is better.

3. Calculating Distance of the Critical Injector-Producer Spacing

It could be calculated from above, the model of areal sweeping efficiency regression was:

$$E_A = 0.972\Delta P_D - 0.001L_D + 0.701 \tag{16}$$

The greater the areal sweep efficiency was, the higher the producing degree of reservoir was, the better development was, because of the heterogeneity of reservoir and flow resistance, the areal sweep efficiency was impossible to achieve 1. Therefore, under the condition of being achieved reservoir effective development, and the range of areal sweeping efficiency should be 0~1.

Figure(4) showed that the injection-production pressure drawdown was fixed, injection and production well spacing and areal sweep efficiency approximate linear relationship, and it was negatively correlated; the greater the pressure of injection and production, the larger limit injector spacing was; under the different layer series of development, the same injection-production pressure drawdown, critical injector producer well spacing was also different, the greater formation permeability was, the larger critical injector producer spacing was.

According to the mathematical model of areal sweep efficiency, given the pressure on the basis of injection and production, when the areal sweep efficiency was taken as 1, there would be the critical injector producer well spacing. When it greater than this injector producer well spacing, then reservoir could be used, this got the critical injector producer well spacing under each pressure of injection and production (Table 2).

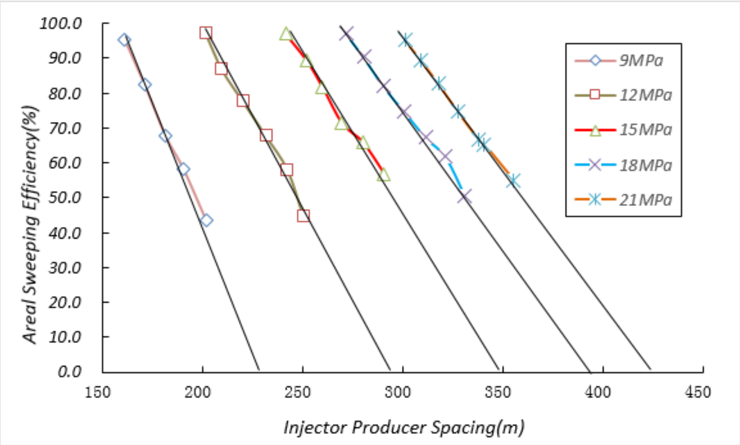

Figure 4. The Relationship of Areal Sweeping Efficiency with Injector-Producer Spacing under Different injection-Production Pressure Difference

Table 2. Limit Injector Spacing under Different Pressure of Injection and Production

Pressure(Mpa)	Critical injector-producer spacing(m)	maximum injector producer spacing(m)
9	160	228
12	203	294
15	241	248
18	278	394
21	301	424

4. Result and Discussion

The critical injector producer well spacing and maximum injector producer well spacing have been marked in Table 1. According to the development of current blocks, the well spacing density is 13 well/km^2, well spacing is 235m at present, the application of some methods such as: oil production rate, single well production, balance of injection and production, Xierkaqiaove formula to determine the reasonable well spacing density is 20.75 well/km^2, well spacing is 219m. The injection production pressure difference in the block concentrated on 10-16Mpa, in current well exist encryption. Besides the water quality, water sensitivity, the current block exists high water injection pressure and difficult to inject, the adjustment of well pattern can relieve the contradiction of exploration in some extent.

In view of single thin reservoir, the calculation on the above only considered the condition of plane homogeneity, plane heterogeneity and gravity were not be considered. Some suggestions on later scholars can analyze and discuss sweep efficiency, expand from two-dimensional space to three-dimensional space, to make the calculation results of thick reservoir are more reliable.

5. Conflict of Interest

The authors confirm that this article content has no conflicts of interest.

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