Application of Layered Perforation Profile Control Technique to Low Permeable Reservoir

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Abstract. It is difficult to satisfy the demand of profile control of complex well section and multi-layer reservoir by adopting the conventional profile control technology, therefore, a research is conducted on adjusting the injection production profile with layered perforating parameters optimization. i.e. in the case of coproduction for multi-layer, water absorption of each layer is adjusted by adjusting the perforating parameters, thus to balance the injection production profile of the whole well section, and ultimately enhance the oil displacement efficiency of water flooding. By applying the relationship between oil-water phase percolation theory/perforating damage and capacity, a mathematic model of adjusting the injection production profile with layered perforating parameters optimization, besides, perforating parameters optimization software is programmed. Different types of optimization design work are carried out according to different geological conditions and construction purposes by using the perforating optimization design software; furthermore, an application test is done for low permeable reservoir, and the water injection profile tends to be balanced significantly after perforation with optimized parameters, thereby getting a good application effect on site.

Keywords. Layered perforating parameters optimization; adjust water injection profile; mathematic model; low permeable reservoir.

1. Introduction
Affected by reservoir heterogeneity after water-flooding, most of the low permeable reservoir forms one-way breakthrough along the high water absorption layer, which leads to premature water breakthrough of some oil wells and brings some difficulty for oilfield development. Water injection profile control is one of important measures for comprehensive management of oilfield. Profile control is usually conducted for oilfield with mechanical or chemical method, however, the stratum is more and more complicated, and the conventional profile control method cannot satisfy the modern demand of profile control. Perforation profile control is to rationally optimize the perforating parameters according to the percolating resistance of oil reservoir in the perforation completion, so as to balance the water injection profile of each layer and realize the purpose of profile control [1-3].
2. Establishment of mathematic model

2.1. Percolating resistance of oil reservoir

Percolation zone of oil reservoir between injection and production well is simplified into 3 flow zones: oil flow dominated oil zone near the oil well zone, water flow dominated water zone near the water well zone, and oil-water coexistence zone. According to the equivalent percolating resistance method and oil-water phase percolation theory, the percolating resistance of oil reservoir is [4-5]:

\[
R_i = \frac{\mu_w \ln \left( \frac{D_o}{D_w} \right)}{2\pi K_w h} + \frac{\mu_{ow} \ln \left( \frac{D_o}{D_l} \right)}{2\pi K_{ow} h} + \frac{\mu_o \ln \left( \frac{D_l}{D_w} \right)}{2\pi K_o h}
\]

(1)

2.2. Determination of the relationship between percolating resistance and perforation skin factor

The resistance adjustment factor refers to the ratio between the total flow resistance of certain layer after perforation adjustment and the non-pollution total flow resistance of the corresponding open hole, and this factor stands for the degree of perforation adjusting resistance:

\[
\sigma = \frac{R_R + R_b + S_t}{R_t + R_b}
\]

(2)

In the formula: \( \sigma \) stands for resistance adjustment factor; \( R_R \) stands for flow resistance of oil reservoir, \( \text{mPa} \cdot \text{s} / (\mu\text{m}^2 \cdot \text{m}) \); \( S_t \) stands for the resistance produced by skin factor from perforation, \( \text{mPa} \cdot \text{s} / (\mu\text{m}^2 \cdot \text{m}) \); \( R_b \) stands for the flow resistance of perforation interval in the wellhole, \( \text{mPa} \cdot \text{s}/(\mu\text{m}^2 \cdot \text{m}) \).

To evaluate the percolating resistance of oil reservoir of unit thickness, the concept of percolating resistance strength \( R_t \) is introduced, and its physical significance means the percolating resistance of oil reservoir of unit thickness. While the resistance strength adjustment factor \( B_{ta} \) refers to the ratio between the base value of certain resistance strength and the percolating resistance of single layer. Resistance strength adjustment factor \( B_{ta} > 1 \) means the resistance of the layer after perforation should increase, which generally happens at the high-permeability layer; resistance strength adjustment factor \( B_{ta} < 1 \) means the resistance of the layer after perforation should decrease, which generally happens at the low-permeability layer.

\[
B_{ta} = \frac{R(i)}{R_t}
\]

(3)

Resistance strength adjustment factor stands for the resistance difference between layers, while resistance adjustment factor means the resistance difference that oil reservoir should reach through perforation; the two should be equal according to the idea of profile control, i.e. \( B_{ta} = \sigma \), and accordingly the calculation formula of perforation skin factor \( S_t \) is:

\[
S_t = (B_{ta} - 1) \left[ \frac{\mu_w \ln \left( \frac{D_o}{D_w} \right)}{2\pi K_w h} + \alpha \frac{\mu_{ow} \ln \left( \frac{D_o}{D_l} \right)}{2\pi K_{ow} h} + \frac{\mu_o \ln \left( \frac{D_l}{D_w} \right)}{2\pi K_o h} \right]
\]

(4)
2.3. Relationship between perforation skin factor and productivity ratio
Suppose that flow around the hole of wellbore is 3D, stable, incompressible flow, conforms to Darcy law, and flow rate flowing towards the well via the hole is evenly distributed in each hole. According to the percolation theory, the finite element method is used to gain the relationship between productivity ratio PRI and perforation skin factor St:

\[ PRI = \frac{\ln\left(\frac{D_r}{D_w}\right)}{\ln\left(\frac{D_s}{D_w}\right) + S_t} \]  

(5)

2.4. Relationship between productivity ratio and perforation parameters
Based on the existing research, nonlinear regression method is applied to regress mass data gained in finite element well perforation model, and according to the comprehensive settlement, the relationship between perforation parameters and productivity ratio under non-pollution and non-compact condition:

\[ PRI = -0.08 + 0.0006228PA + 0.0054DEN + 0.015665PD + 0.0031PHA + 0.00208D_w + 0.05155\frac{K_s}{K_h} - 0.0032596\frac{K_s}{K_h} \cdot D_w - 0.00001656PHA^2 \]  

(6)

In the formula: PRI stands for productivity ratio; PA stands for hole depth, cm; DEN stands for hole density, hole/m; PD stands for hole diameter, mm; Ks/Kh stands for the ratio between the vertical permeability and longitudinal permeability; PHA stands for phase, (°); Dw stands for downhole diameter, m.

2.5. Mathematic model of injection production profile control with layered perforating parameters optimization
According to an analysis on the influence of percolating resistance of oil reservoir, resistance adjustment factor of individual reservoir and perforating parameters on productivity, a mathematic model formula (7) of injection production profile control with layered perforating parameters optimization is built based on formula (4)~(6), thus providing favorable theoretical basis[7] for rational perforating parameters of each single layer at the well completion stage during layer mining.

\[ f(R) = -0.08 + 0.0006228PA + 0.0054DEN + 0.015665PD + 0.0031PHA + 0.00208D_w + 0.05155\frac{K_s}{K_h} - 0.0032596\frac{K_s}{K_h} \cdot D_w - 0.00001656PHA^2 \]  

(7)

In the formula: f(R) stands for the function of stratum and fluid property parameters.

The relation between perforating parameters and resistance adjustment factor of individual reservoir is built in formula (7), besides, the perforating parameters can be optimized and combined through this model [8-9].

3. Programming of hole depth/hole density optimization software
On the basis of research on perforating parameters optimization methodology and establishment of mathematic model, “hole depth/hole density optimization related perforation profile control software” is developed on the principle of “reservoir protection and enhanced oil recovery”. This software is
characterized by correct running, convenient operation, and high degree of engineering and practical application [9-10].

3.1. Software programming principle
Percolating resistance of each single layer is calculated first to find out the producing pay with the largest percolating resistance. The designated market bed method is adopted to set the perforation density of the producing pay with the largest percolating resistance as the largest perforation density of the whole well section, while for other layers, the theoretically rational perforation density is reasonably matched for each layer according to the size of its percolating resistance strength, resistance adjustment factor and resistance strength adjustment factor.

3.2. Characteristics and functions of the software
Hole depth/hole density perforation optimization software, based on the research on perforating parameters optimization methodology and establishment of mathematic model, is to forecast the reasonable combination of perforating parameters- hole depth and hole density regarding different operation reservoirs and different perforating guns and bullets with the productivity ratio of perforation well as target. The perforating parameters are optimized through this software, and that with high productivity ratio and low casing strength reduction value is determined as the optimal perforation scheme [11-12]. This software has open software function, and the user can add, delete, update the data in database according to the practical truth, and it is featured by friendly interface, strong operability, convenient and rapid application.

4. Field application of the software
According to the above theories and methods, a test was conducted for several wells on the field with the programmed perforation parameters optimization software. Data and optimization result of single layer at each well section of two wells in the optimized block are shown in Table 1 and Table 2.

| Serial number | Single layer number | perforated interval /m | effective thickness /m | effective permeability /10^-3 μm^2 | Optimization hole depth /cm | Optimization shooting density /(pore/m) |
|---------------|---------------------|------------------------|------------------------|-------------------------------|-----------------------------|--------------------------------------|
| 1             | 4-75                | 990.1–987.9            | 2.2                    | 33–45                         | 45                          | 9                                    |
| 2             | 4-75                | 987.9–982.7            | 1.7                    | 4–20                          | 56                          | 15                                   |
| 3             | 4-73                | 981.9–981.4            | 0.5                    | 6–11                          | 90                          | 16                                   |
| 4             | 4-72                | 979.3–978.8            | 0.5                    | 11–23                         | 87                          | 13                                   |
| 5             | 4-71                | 978.1–977.6            | 0.5                    | 15–27                         | 80                          | 12                                   |

| Serial number | Single layer number | perforated interval /m | effective thickness /m | effective permeability /10^-3 μm^2 | Prediction hole depth /cm | Prediction shooting density /(pore/m) |
|---------------|---------------------|------------------------|------------------------|-------------------------------|-----------------------------|--------------------------------------|
| 1             | 4-73                | 1004.4–999.8           | 2.2                    | 31–40                         | 49                          | 9                                    |
| 2             | 4-73                | 999.8–995.2            | 1.5                    | 3–21                          | 53                          | 13                                   |
| 3             | 4-72                | 997.3–995.0            | 1.2                    | 7–12                          | 65                          | 15                                   |
| 4             | 4-71                | 993.6–993.1            | 0.5                    | 4–10                          | 83                          | 16                                   |

As can be seen from Table 1 and Table 2, the optimized result properly shows the idea of adjusting perforating parameters of each layer based on the permeability heterogeneity of each single layer, and
also indicates that the result optimized by this software can meet the requirement of accuracy and practicality. In order to intuitively understand the filed application effect of the perforation with optimized parameters, the water absorption condition of each single layer before and after optimization of the two wells is made (FIG. 1 and FIG. 2).

As can be seen from FIG. 1 and FIG. 2, after perforation with optimized parameters, the range of difference of water absorption of each single layer is greatly shortened, and water absorption of each layer tends to be balanced significantly. The adoption of optimization technique obviously improves the uneven original water injection profile, and promotes the producing degree of profile, this is because the optimized perforating parameter adjusting profile technique can improve the percolation condition of each layer of perforation well, and accordingly increase the effective permeability of reservoir and effective radius of down hole, therefore, this technique can guide the formulation of perforation scheme for the field in a better way.

![Fig. 1 Change of water absorption before and after optimization for No. 2 well](image1.png)

![Fig. 2 Change of water absorption before and after optimization for No. 1 well](image2.png)


5. Conclusion

(1) Based on the idea of adjusting the injection production profile with perforating parameters optimization, the mathematic model of injection production profile control with perforating parameters optimization is built, and this model is a simple and practical tool for reservoir engineer to analyze and determine the perforating parameters of each layer.

(2) On the basis of research on perforating parameters optimization methodology and establishment of mathematic model, perforating parameters optimization software is programmed. This software is characterized by correct and reliable running, strong practicability, simple operation and friendly interface.

(3) After perforation with optimized parameters, water absorption of each layer tends to be balanced significantly, which obviously improves the uneven original water injection profile and promotes the producing degree of profile, and accordingly the test obtains an ideal effect.

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