Study on the optimization of timing for horizontal well re-fracturing in tight oil reservoir -- A case study of Baikouquan Formation in North Mahu Oilfield, Junggar Basin, Western China

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Abstract. There are abundant tight oil resources in China, and "horizontal well + volume fracturing" technology is the one of the main means to develop such reservoirs. The production of tight oil reservoir declines generally rapidly after the initial fracturing, therefore it is necessary to be conducted re-fracturing operation to restore the oil productivity. The determination of the best time of re-fracturing is an important factor to ensure the re-fracturing effect. In this paper, a mathematical model of oil-water phase seepage was established by applying the principle of finite difference method (FDM). A unified grid system was adopted for the division of the matrix and fractures, and the equations were solved by the IMPES method. The reliability of the proposed seepage model gets verified by the historical matching based on the field production data. The oil production after re-fracturing at different moments of time after initial fracturing was predicted. The simulations show that more cumulative oil production can be obtained if re-fracturing is implemented after the fourth year of initial fracturing. During the period after the 4th year of the initial fracturing, the earlier the re-fracturing is implemented, the more the cumulative oil production will be harvested. Considering the cost of re-fracturing operation, the economic benefits of re-fracturing after the sixth year of initial fracturing were evaluated. The results show that the cost can be recovered about one year after the re-fracturing, the net present value (NPV) after four years of re-fracturing reaches 69.95 million yuan, with an output-input ratio of 5.3.

1. Introduction

There is a great prospect for the exploration and development of tight oil in the unconventional oil and gas field. The large oil-gas basins in China, such as Ordos, Junggar, Songliao, and Qaidam, are rich in tight oil resources [1-3]. In recent years, "horizontal well + volume fracturing" technology has gradually become one of the main means to develop tight oil reservoirs, which greatly improves the production of tight oil [4]. However, due to the poor physical properties of tight oil reservoirs, the formation energy drops sharply along with the oil exploitation. However, an effective injection-production pattern can not be formed for horizontal wells, resulting in insufficient
replenishment of energy. What’s worse, under the action of fracture closure, the proppants deform, embed and break, resulting in the rapid decline of fracture conductivity. Because of this, some hydraulic fractures in horizontal wells will be invalid, causing rapid decline of oil production and shortened stable production period [5]. In order to recover the productivity of such horizontal wells, the re-fracturing technology is considered as one of the most potential and currently most widely-used measures to stimulate the oil and gas production [6].

In the 1950s, researchers began to carry out the study on vertical well re-fracturing, while the research on horizontal well re-fracturing started relatively later. Since the 21st century, thanks to the large-scale development of shale gas, more and more attention began to be focused on the research on horizontal well re-fracturing [7]. The determination of the timing of re-fracturing is an important aspect in the research of horizontal well re-fracturing. That is, to answer the question of when to implement the re-fracturing to achieve the best oil and gas stimulation effect from the horizontal wells. In the case of the vertical well re-fracturing, it is generally considered that the best timing for re-fracturing is the moment when the change of the ground stress becomes the strongest. Since during this time, the re-fracturing can effectively improve the sweep efficiency and reduce the dead oil area. When it comes to the horizontal well, there are many factors that affect the timing of the re-fracturing. In this case, numerical simulation is usually used to optimize the timing of the horizontal well re-fracturing, with the cumulative oil production or net present value (NPV) being usually taken as the objective function.

Lantz et al. (2008) [8] found that the optimal timing of horizontal well re-fracturing in Bakken shale oil reservoirs changes depending on the completion conditions of the initial fracturing and the difference of the re-fracturing technology. Generally speaking, the effect of re-fracturing is at its best level in 2 to 3.5 years after the initial fracturing. Tavasoli et al. (2013) [9] improved the CMG model and established a numerical model to predict the timing of re-fracturing by the use of the daily gas production and cumulative gas production as the optimization goals. The results indicate that the best effect of re-fracturing is achieved when the gas production falls to 10% - 15% of the initial production. Based on the three different price prediction models of natural gas, Cafaro (2016) [10] did the optimization by taking net present value (NPV) as the objective function and found the optimal frequency and timing of re-fracturing of shale gas horizontal wells corresponding to each price change trend. Based on the finite element method (FEM), Pang et al. (2015) [11] established the mathematical model of oil-water phase seepage, and predicted the daily oil production change of a horizontal well in Changqing Oilfield conducted by re-fracturing after the initial fracturing in the 5th, 6th, 7th and 8th years respectively. By taking the cumulative oil production as the optimization target, 7 years after the initial fracturing was selected as the optimal timing for the re-fracturing operation.

The Baikouquan Formation, locating at North Mahu Oilfield, Junggar basin, China is composed mainly of low permeable glutenite rock, where is rich in tight oil resources. The development mode of "horizontal well + volume fracturing" has been applied widely there. The production of some of those horizontal wells has declined seriously and need to be conducted re-fracturing [12]. However, North Mahu Oilfield does not have the practical experience of re-fracturing before, and there is no previous research on the optimization of the timing for horizontal well re-fracturing aiming at this oilfield. In this paper, taking Well X as a case for study, the oil-water phase seepage model was established, and the equations were discretized based on the finite difference method (FDM) to establish the numerical model, and the equations were solved by Implicit Pressure Explicit Saturation (IMPES) method. This model can be used to calculate the change of oil production after re-fracturing with different timing, and to evaluate the economic benefits of Well X after re-fracturing with the cost of re-fracturing taken into consideration.

2. Establishment of mathematical model

2.1. Model hypothesis

- The reservoir is rectangular, and the flow of fluid is isothermal seepage.
• Two dimensional plane flow (ignoring the influence of fluid gravity).
• There is only oil and water two-phase seepage in the reservoir, and the oil and water do not dissolve each other, and each conforms to Darcy's law.
• Both rock and fluid can be compressed.
• The heterogeneity and anisotropy of rock is considered.
• The capillary force of oil and water is considered.
• The hydraulic fracture extends completely through the reservoir, with the fracture height equal to the reservoir thickness.

2.2. Seepage equations

2.2.1. Reservoir matrix system

The differential equations of oil-water two phase seepage:

\[
\frac{\partial}{\partial x} \left( \rho_o \frac{k_{ro} \cdot \partial p_o}{\mu_o} \right) + \frac{\partial}{\partial y} \left( \rho_o \frac{k_{ro} \cdot \partial p_o}{\mu_o} \right) = \frac{\partial}{\partial t} (\varphi p_o s_o) \tag{1}
\]

\[
\frac{\partial}{\partial x} \left( \rho_w \frac{k_{rw} \cdot \partial p_w}{\mu_w} \right) + \frac{\partial}{\partial y} \left( \rho_w \frac{k_{rw} \cdot \partial p_w}{\mu_w} \right) = \frac{\partial}{\partial t} (\varphi p_w s_w) \tag{2}
\]

where \( k \) [\( \mu \text{m}^2 \)] is the absolute permeability of formation, \( k_{ro} \) is the relative permeability of oil phase, \( k_{rw} \) is the relative permeability of water phase, \( \mu_o \) [\( \mu \text{Pa·s} \)] is the oil viscosity, \( \mu_w \) [\( \mu \text{Pa·s} \)] is the water viscosity, \( s_o \) is the oil saturation, \( s_w \) is the water saturation, \( p_o \) [MPa] is the pressure of oil phase, \( p_w \) [MPa] is the pressure of water phase, \( \varphi \) is the formation porosity.

The auxiliary equations are:

\[ P_c = p_o - p_w \tag{3} \]

\[ s_o + s_w = 1 \tag{4} \]

The initial conditions are:

\[ p_w(x, y, 0) = p_i \tag{5} \]

\[ s_w(x, y, 0) = s_{wi} \tag{6} \]

The closed outer boundary conditions of matrix system are:

\[
\left( \frac{\partial p_o}{\partial x} \right)_{y=0} = 0
\]

\[
\left( \frac{\partial p_o}{\partial x} \right)_{y=L_y} = 0
\]

\[
\left( \frac{\partial p_w}{\partial y} \right)_{y=0} = 0
\]

\[
\left( \frac{\partial p_w}{\partial y} \right)_{y=L_y} = 0
\]

The inner boundary condition of matrix system is under the constant flowing bottomhole pressure (FBHP):
\[ p_{wf} = C \]  
\[ p_i \text{ [MPa]} \] is the capillary pressure, \( p_i \text{ [MPa]} \) is the initial formation pressure, \( s_{wi} \) is the initial water saturation, \( p_{wf} \text{ [MPa]} \) is the FBHP.

2.2.2. Fracture system

For the fracture system, the fluid flow is considered as one-dimensional, and the capillary force in the fracture is not considered. Therefore, the oil-water phase seepage equations of the fracture system are expressed as:

\[
\frac{\partial}{\partial x} \left( \rho_o \frac{k_f k_m}{\mu_o} \frac{\partial p_o}{\partial x} \right) = \frac{\partial}{\partial t} \left( \phi p_o s_o \right) 
\]

(9)

\[
\frac{\partial}{\partial x} \left( \rho_w \frac{k_f k_{rw}}{\mu_w} \frac{\partial p_w}{\partial x} \right) = \frac{\partial}{\partial t} \left( \phi p_w s_w \right) 
\]

(10)

The initial conditions are:

\[ p_i (x, 0) = p_i \]  
(11)
\[ s_w (x, 0) = s_{wi} \]  
(12)

The closed outer boundary conditions of fracture system are:

\[
\left( \frac{\partial p_f}{\partial x} \right)_{x=0} = 0 
\]

\[
\left( \frac{\partial p_f}{\partial x} \right)_{x=L_f} = 0 
\]

(13)

The inner boundary condition of fracture system is under the constant FBHP:

\[ p_{wf} = C \]  
(14)

2.3. Discretization and solution of the equations

In order to satisfy the flow continuity, the pressure balance and the calculation of matrix and fracture systems, a unified grid system is adopted for the division of the matrix and fracture. As the width of the fracture differs by several levels of magnitude when compared with the grid size, the matrix and fracture grids are uniformly divided along the fracture direction, which is shown in figure 1. The five diagonal matrix equations are obtained by the central differentiation of the oil and water seepage differential equations. By selecting \( p_o \) and \( s_w \) as independent variables, and using the IMPES method to solve it, that is, use the implicit iterative method to solve \( p_o \), and use the explicit iterative method through “one-step pressure, multi-step saturation” to solve \( s_w \).
The production of oil flowing from the fracture into the well is:

\[
q_{of}(i, j) = \frac{k_f k_o w_f}{\mu_o B_o \ln(r_e / r_w) + S} \left( \frac{p_f(i, j) - p_w}{2} \right)
\]

where \(k_f\) [μm²] is the fracture permeability, \(w_f\) [m] is the fracture width, \(S\) is the skin factor, \(B_o\) is the oil volume factor, \(r_e\) [m] is the apparent grid radius, \(r_w\) [m] is the wellbore radius.

3. Model verification

3.1. Physical model of initial fracturing

Well X is an open-hole horizontal well deployed in the Baikouquan Formation, North Mahu Oilfield. The horizontal section is 800m at length, and 14 hydraulic fractures are generated after the initial fracturing. The production of this well decreases rapidly after the initial fracturing, therefore it is necessary to carry out the re-fracturing. The physical model of production prediction after the initial fracturing of Well X is established, as shown in figure 2, in which the red straight line represents the hydraulic fracture, the thicker black straight line symbolizes the wellbore, with a model area of 1600m × 600m.

3.2. Input parameters

The input reservoir parameters for the production prediction after the initial fracturing of Well X can be seen in Table 1. According to the fracture simulation and the potentiometry monitoring results, the length, conductivity and the average fracture width of all the fractures created by initial fracturing in Well X can be calculated, with the results shown in table 2. By inputting the above parameters into the model, the oil production after initial fracturing can be calculated.
Table 1. Reservoir parameters for production prediction of Well X after initial fracturing

| Parameter name                          | Unit    | Value     | Parameter name                          | Unit     | Value     |
|-----------------------------------------|---------|-----------|-----------------------------------------|----------|-----------|
| Formation pressure                      | MPa     | 44.8      | Initial water saturation                | %        | 48.57     |
| Porosity                                | %       | 9.42      | Rock compression coefficient            | MPa⁻¹    | 3×10⁻⁴    |
| Permeability                            | μm²     | 1.16×10⁻³ | Water compression coefficient           | MPa⁻¹    | 4.5×10⁻⁴  |
| Temperature                             | °C      | 81.8      | Oil compression coefficient             | MPa⁻¹    | 8.4×10⁻⁴  |
| Effective reservoir thickness            | m       | 12.0      | Water volume factor                     | Dimensionless | 1.0      |
| Oil volume factor                       | Dimensionless | 1.1      | Oil viscosity                           | mPa·s    | 8.04      |
| Oil density                             | kg/m³   | 800       | Oil-water relative permeability curve   | /        | See the fitting curve in figure 3 |

Figure 3. Oil-water relative permeability curve of Well X
### Table 2. Fracture parameters of initial fracturing of Well X

| No. | Half-length of fracture (m) | Initial average fracture conductivity (D·cm) | Average fracture width (mm) |
|-----|-----------------------------|---------------------------------------------|-----------------------------|
| 1   | 160                         | 59.7                                        | 6.8                         |
| 2   | 150                         | 68.8                                        | 9.1                         |
| 3   | 140                         | 60.9                                        | 7.5                         |
| 4   | 130                         | 68.7                                        | 5.1                         |
| 5   | 150                         | 58.3                                        | 2.9                         |
| 6   | 120                         | 73.0                                        | 5.1                         |
| 7   | 130                         | 58.3                                        | 3.2                         |
| 8   | 120                         | 59.4                                        | 3.2                         |
| 9   | 140                         | 61.3                                        | 5.1                         |
| 10  | 90                          | 56.5                                        | 6.1                         |
| 11  | 140                         | 58.5                                        | 6.8                         |
| 12  | 150                         | 68.6                                        | 5.5                         |
| 13  | 130                         | 59.1                                        | 8.3                         |
| 14  | 130                         | 69.7                                        | 6.5                         |

3.3. **Historical fitting of the oil production**

Well X was conducted initial fracturing 5.5 years ago, i.e., about 1960 days. By adjusting the parameters such as the oil-water relative permeability relationship, the curve of predicted oil production is consistent with the curve of actual oil production. After adjustment, the curve of predicted daily oil production and actual daily oil production in relation to time after the initial fracturing is obtained and shown in figure 4. Also, the corresponding cumulative oil production can be calculated accordingly, as shown in figure 5. It can be seen that the trend of the curve of predicted accumulative oil production is consistent with that of the actual accumulative production.

![Figure 4. The change curve of daily oil production after initial fracturing of Well X](image)
Figure 5. The change curve of cumulative oil production after initial fracturing of Well X

The established mathematical model is used to predict the formation pressure distribution of 1 month and 5.5 years respectively after the initial fracturing of Well X, with the results shown in figure 6 and figure 7. It can be seen that the formation pressure around the intersection of the wellbore and the fracture is about 28.1MPa, while the FBHP measured by downhole pressure gauge in Well X one month after initial fracturing is 29.1MPa (the data is sourced from the daily production report of Well X), which is close to the prediction result of model 28.1MPa, with an error rate of 3.4%. This verifies the accuracy of the established model in this paper. After that, along with the continuous exploitation of crude oil, although there is small amount of change in the formation pressure around the wellbore, the low-pressure area gradually spreads to the area between the fractures and the direction of fracture tips, which eventually forms an elliptical low-pressure area with the long axis parallel to the fracture direction 5.5 years later, with the pressure value of the low-pressure area being about 26 MPa.

Figure 6. The formation pressure distribution 1 month after the initial fracturing
4. Optimization of re-fracturing timing

4.1. Physical model and input parameters of re-fracturing

By substituting the fracture parameters and the updated boundary conditions of the re-fracturing design into the established model, we can calculate the oil production change after re-fracturing implemented at different moments of time after the initial fracturing. According to the re-fracturing plan of Well X, in addition to the re-fracturing of the original 14 old fractures, based on the logging interpretation results, 6 locations in the horizontal section were selected for perforating new holes, and 6 new fractures were created at these locations. In this paper, the oil production of Well X after re-fracturing in the 3rd, 4th, 5th, 6th and 7th year after the initial fracturing are simulated respectively, and the calculation time is totally 10 years after the initial fracturing.

The physical model of re-fracturing production prediction is shown in figure 8, in which the red line represents the old fracture and the blue line represents the new fracture. According to the software simulations, the average conductivity of the old fracture after re-fracturing is 48.04D cm, with the average fracture width of 4.52mm; the average conductivity of the new fracture is 60.18dD cm, with the average fracture width of 5.26mm.

4.2. Results of predicted oil production

4.2.1. Daily oil production

Figure 9 shows the prediction curves of daily oil production after re-fracturing at different times after the initial fracturing of Well X. It can be seen that the daily oil production capacity of Well X has been rapidly recovered no matter when the re-fracturing is carried out. The maximum daily oil production
can reach 40m³/d at the initial stage, and then the daily oil production is rapidly reduced. Generally, the oil production tends to become stable 2 years after the re-fracturing is implemented. Moreover, the stable daily oil production after re-fracturing is higher than that without re-fracturing.

4.2.2. Cumulative oil production

Figure 10 shows the prediction curves of cumulative oil production after re-fracturing at different times after the initial fracturing of Well X. Table 3 indicates the cumulative oil production in 10 years after the initial fracturing. It can be seen that when re-fracturing is implemented after the 4th year of the initial fracturing, the cumulative oil production is higher, implying that it is the best time to implement the re-fracturing after the fourth year. It can be concluded from figure 10 that after the fourth year of initial fracturing, the earlier the re-fracturing is implemented, the higher the cumulative oil production will be obtained. It has been 5.5 years since the initial fracturing of Well X. Although that means Well X has missed the best opportunity for re-fracturing, according to the production prediction results, the earlier the re-fracturing is, the more oil harvest is.
Table 3. 10-year cumulative oil production obtained after re-fracturing at different times after initial fracturing of Well X

| Time interval between initial fracturing and re-fracturing (year) | 10-year cumulative oil production (m³) |
|---------------------------------------------------------------|-------------------------------------|
| No re-fracturing                                              | 41037                                |
| 3                                                             | 57306                                |
| 4                                                             | 61427                                |
| 5                                                             | 59009                                |
| 6                                                             | 57659                                |
| 7                                                             | 54168                                |

5. Evaluation of the economic benefits

Although the application of re-fracturing in horizontal wells can increase the oil production notably, the operation of re-fracturing needs to spend a certain cost. According to the design scheme of Well X, the amount of fracturing fluid, proppant, temporary plugging agent and other materials can be known, and the cost of fracturing materials can be estimated based on the market price. By taking the rental cost of equipment and the labor cost into consideration, the total cost of implementing re-fracturing of Well X is estimated to be 16.28 million yuan. For the crude oil produced by re-fracturing, based on the international oil price of 70 US dollars/barrel and the exchange rate at 6.9 US dollars, the price of crude oil can be calculated to be about 2900 yuan/m³, the income after the sale of crude oil at different times after re-fracturing can be calculated.

The economic benefit of refracturing is evaluated by net present value (NPV) and output/input ratio ($\eta$). The formulas are:

$$\text{Net present value (NPV)} = \text{Total present value of future return} - \text{Initial investment} \quad (16)$$

$$\text{Output/input ratio } (\eta) = \frac{\text{Crude oil sales income}}{\text{Cost of re-fracturing}} \quad (17)$$

Since Well X has been exploited for 5.5 years, although the best opportunity for re-fracturing has been missed, it is still that the earlier the re-fracturing is implemented, the better the effect will be. Therefore, the NPV curve and the output/input ratio curve of re-fracturing after the 6th year after the initial fracturing are calculated and drawn, as shown in figure 11 and figure 12.

As known from figure 11, the cost can be recovered in about one year after re-fracturing. After 350 days of exploitation, NPV acquired from re-fracturing began to catch up and even surpass the NPV from those without re-fracturing. 4 years after the re-fracturing (that is, 10 years after the initial fracturing), the NPV reaches 69.95 million yuan. If no re-fracturing was carried out, NPV would be only 38.03 million yuan. Therefore, compared with non-refracturing, NPV after re-fracturing increased 31.92 million yuan. It can be seen from figure 12 that 4 years after the re-fracturing (i.e., 10 years after the initial fracturing), the output input ratio reaches 5.3.
6. Conclusion

- The mathematical model of oil-water phase seepage is established, with the matrix and fracture divided by a unified grid system, and the equations are discretized based on the FDM method and is solved by IMPES method.

- In the study case of Well X, by adjusting the parameters such as the relation of oil-water phase permeability, the rule of change of the predicted oil production curve obtained by fitting is basically consistent with that of the actual oil production curve. The predicted results of formation pressure decline are consistent with the testing results of downhole measurement by pressure gauge, which verifies the accuracy of the established model.

- The numerical simulation results indicate that more cumulative oil production can be realized after the 4th year of initial fracturing of Well X, which reaches 61427m³. Although the best time of re-fracturing has been missed in Well X, it is recommendable that the re-fracturing should be carried out as early as possible. Considering the cost of re-fracturing operation, the NPV reaches 69.95 million yuan after 4 years since the re-fracturing (that is, 10 years after the initial fracturing), with an output-input ratio reaching 5.3.

Acknowledgments

The research was supported by the Sichuan Science and Technology Project (18YYJC1108) and the cooperative project “Research on temporary plugging volume fracturing for horizontal wells and its field application” between PetroChina Xinjiang Oilfield Company and Beijing Gepetto Petroleum Technology Co., LTD.
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