Optimization of target segment parameters of fishbone horizontal well based on genetic algorithm

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Abstract: The optimization of target parameters of the fishbone horizontal wells is the key to improving single well production capacity and development results. Therefore, in order to improve the development of the fishbone horizontal wells, it is very important that influencing rules of the target segment parameters of the fishbone horizontal well on their production capacity should be studied, and the optimization methods of target segment geometric parameters and wall inflow control parameters are given to achieve the maximum production capacity of horizontal barbed wells and the homogenization of the inflow profile of the target segment. Based on the equivalent caliper model, this study establishes a coupling model between seepage and wellbore tubular flow in fishbone horizontal well reservoirs, and analyzes the effects of target segment parameters on the fishbone horizontal well productivity and the inflow profile of the target segment. Combined with the genetic algorithm, The segmental optimization method for the inflow control parameters of the target segment wall solves the problem of scientific optimization design of the perforation parameters of the target segment of the fishbone horizontal wells. The research shows that the inhomogeneity of the permeability along the wellbore is the main influencing factor for the optimal design of the inflow control parameters of the target section, and the impact on the inflow profile of the target section is more sensitive than the pressure drop of the wellbore; the perforation density of the high-permeability target section after optimization is small. The perforation density of the low-permeability target segment is large, thereby reducing the inflow velocity of the high-penetration target segment, increasing the inflow velocity of the low-penetration target segment, and maximizing the uniform inflow of the target segment.

1. Instruction
At present, there are few researches on the optimal design of the target well section parameters in heterogeneous reservoirs. In 1991, Landman [1] considered the borehole as a finite diversion pipe, established an optimization model of the perforation distribution in the target section of the horizontal well, analyzed the distribution regularity of the hole density under the condition of uniform inflow, but did not consider formation pollution and perforation compaction. In 1993, Marett [2] comprehensively considered the formation pollution, perforation compaction, well angle, etc., substituting perforation completion skin factor into wellbore and reservoir coupling model, established perforation parameter optimization model of target section, and analyzed well inclination, the influence of angle and permeability heterogeneity on the distribution of perforation density. In 1997 Asheim [3] divided the entire flow pressure drop into the flow pressure drop to the well, the flow pressure drop of the borehole, and the pressure drop of the wellbore. The hole was regarded as the microelement well section, and the pressure drop was calculated for each flow and then established target perforation
parameter optimization model according to the pressure continuously. In 2001 Zhou Shengtian[4-6] studied the distribution of horizontal perforation hole density along the target segment using a similar method to that of Asheim. In 2005, Wang Zhiming[7-9] studied the gas-liquid two-phase flow homogeneous reservoir in the wellbore under the condition that the perforation density of the target section is optimized. In 2007 Wang Shuping[10] studied the effect of the perforation distribution pattern on the inflow profiles of horizontal wells. None of these studies have achieved segment optimization target section perforation parameters in permeability under heterogeneous conditions.

Based on the equivalent caliper model, this study established a coupling model of seepage and wellbore tubular flow in the fishbone horizontal wells reservoirs. Combined with the genetic optimization algorithm, a segmentation optimization method for the inflow control parameters of the target segment wall was presented, and the target section perforation parameters of the fishbone horizontal well science optimizes design issues was solved.

2. Reservoir and wellbore coupling model establishment

2.1 Fishbone Horizontal Well Reservoir Seepage Model.

The flow of fluid from the reservoir into the wellbore can be divided into two zones, away from the target segment area and the target segment near well inflow zone. The inhomogeneity of permeability far away from the target segment has little influence on the inflow profile and can be approximated as a homogeneous oil reservoir; The inhomogeneity of permeability in the near-wellbore inflow zone of the target segment is very sensitive to the inflow profile, and the influence of inhomogeneity of permeability in the near-wellbore inflow zone on the inflow profiles must be considered. Assume that the oil layer is of equal thickness, the fluid is a single-phase incompressible Newtonian fluid, and isothermal flow.

\[ r_{\text{sc,ij}} = \Delta l_j \exp \left( -1.75 + \frac{h}{\Delta l_j} \left( \frac{K_x}{K_v} \ln \left( \frac{\pi r_i}{h} \left( 1 + \frac{K_x}{K_v} \sin \frac{\pi z_j}{h} \right) + \frac{2h^2}{h} \frac{K_x}{K_v} \left( \frac{1}{3} - \frac{z_j}{h} + \frac{z_j^3}{3h^3} \right) \right) - \frac{h}{\Delta l_j} \left( \frac{K_x}{K_v} S_{ij} \right) \right) \]

According to the principle of potential superposition, taking the special points at the supply boundary and the wellbore wall, the relationship between bottom hole pressure and flow at different positions in the target segment of the horizontal spurs of the fish spurs is:

\[ p_e - p_{\text{wt,ij}} = \frac{\mu}{2\pi h K_v} \sum_{n=1}^{N} \sum_{m=1}^{M} \Delta l_m q_{\text{sw,um}} \ln \left( \frac{r_e}{r_{\text{nn,ij}}} \right) \]
\[ r_{nm,ij} = \begin{cases} \sqrt{(x_{nm} - x_{ij})^2 + (y_{nm} - y_{ij})^2} & (i \neq n \neq j \neq m) \\ r_{we,ij} & (i = n \land dj = m) \end{cases} \]

Among them, \( r_{we,ij} \) —— Equivalent well radius of the j micro-section of the i branch target segment, \( m \); \( \Delta l_{ij} \) —— The length of the j micro element segment of the i branch target segment, \( m \); \( h \) —— Reservoir thickness, \( m \); \( K_v \) —— Horizontal permeability, \( 10^{-3} \mu m^2 \); \( K_h \) —— Vertical permeability, \( 10^{-3} \mu m^2 \); \( r_w \) —— Target section wellbore radius, \( m \); \( r_e \) —— Supplying radius, \( m \); \( \mu \) —— Fluid viscosity, \( mPa.s \); \( p_e \) —— Supplying pressure, \( MPa \); \( p_{wf} \) —— Bottom hole pressure, \( MPa \); \( N \) —— Number of branches, number; \( M_i \) —— The number of segments in the i branch target segment, segment; \( z_{ij} \) —— The coordinates of the j meta segment of the i branch target segment in the z direction, \( m \); \( x_{ij} \) —— The coordinates of j the meta segment of the i branch target segment in the x direction, \( m \); \( y_{ij} \) —— The coordinates of the j meta segment of the i branch target segment in the y direction, \( m \); \( S_{ij} \) —— The skin factor of the j meta segment of the i branch target segment, no dimension; \( \theta_{ij} \) —— The well angle of the j meta segment of the i branch target segment; \( p_{wf,ij} \) —— The bottom hole pressure of the j meta segment of the i branch target segment, \( MPa \); \( q_{ws,ij} \) —— Flow velocity of the j meta segment of the i branch target segment, \( m^3/(d.m) \); \( r_{nm,ij} \) —— The distance from the m meta segment of the n branch target segment to the j meta segment of the target segment of the i branch, \( m \).

2.2 Fishbone Horizontal Wellbore Flow Model.

According to the wellbore variable mass flow pressure drop model \([15]\), the wellbore pressure drop at the j micro-section of the i branch target segment of the horizontal spurs of the fish spurs can be expressed as:

\[ p_{wt,ij} - p_{wt,(i-1)} = \Delta p_{acc,ij} + \Delta p_{wall,ij} + \Delta p_{g,ij} = \frac{32 \rho f_j q_{w,j}^2 \Delta l_{ij}}{\pi^2 d_w^4} + \frac{32 \rho q_{ws,ij} \Delta l_{ij}}{\pi^2 d_w^4} + \rho g \cos \theta_j \cdot \Delta l_{ij} + \sum_{n=1}^{N} (q_{ws,in} \Delta l_{in}) \]

Among them, \( q_{ws,ij} \) —— Sectional flow at the j micro-section of the i branch target segment, \( m^3/d \); \( f_j \) —— Wall friction coefficient at the j micro-section of the i branch target segment, no dimension; \( \rho \) —— Fluid density, \( g/cm^3 \); \( d_w \) —— Target section wellbore diameter, \( m \); \( g \) —— Gravity acceleration, \( m/s^2 \).

2.3 Fishbone horizontal well reservoir and wellbore coupling model.

According to the principle of continuous pressure, the pressure at the wellbore of the multi-branch horizontal well of a fishbone spine and the wellbore flow at the wellbore wall should be equal. The available coupling model is:

\[ A_1 X_1 = b_1 \]
\[ A_2 X_2 = b_2 \]

3. Analysis of Influence Rule of Target Segment Geometric Parameters on Productivity

In order to analyze the effect of the geometric parameters of the target segment of the fishbone horizontal well on its productivity, make the reservoir thickness \( h \) is 10.0m. The target zone is at a height of 5.0m from the bottom of the reservoir. The horizontal permeability \( K_h \) is 1000.0mD. The vertical permeability \( K_v \) is 300.0mD. Reservoir supply pressure \( p_e \) is 18.0 Mpa. The bottom hole \( p_{wf} \) pressure is 17.0 Mpa. The reservoir supply radius is 1000.0m. The average fluid density \( \rho \) is 9.5g/cm³. The fluid viscosity \( \mu \) is 20.0mPa.s The all target segment skin factor is 0.0. The target section casing diameter is 139.7 mm.
Figure 3: Relationship between productivity index and branch number of fishbone horizontal wells

Figure 4: Fishbone horizontal well layout

Figure 5: Relationship between horizontal well productivity index of fishbone and angle between branch and main shaft

4. Partial optimization of inflow control parameters for target section wall

(1) Optimization

Based on the coupling model of seepage and wellbore flow in the horizontal wellbore reservoir, the completion skin model\(^{[16]}\) , and the inflow control principle of the wall surface, combined with the actual engineering technical requirements, the optimization steps for the inflow control parameters of
the target segment wall are given as follows:

① According to the permeability value $K(x)$ interpreted by well log at different positions in the target segment, the average value of permeability is calculated as $\overline{K}$.

② Using the coupled model of seepage flow in wellbore horizontal wells and wellbore flow, we calculated the average inflow velocity distribution $q_{\text{w}}(x)$ at different positions of the target segment under ideal conditions of infinite flow guidance for homogeneous reservoirs with an average permeability value of $\overline{K}$.

③ Using the coupled model of seepage and wellbore flow in the fishbone horizontal wellbore reservoir, the uniform inflow velocity distribution $q_{\text{w}}(x)$ at different positions in the target segment, calculate the uniform inflow velocity distribution apparent skin factor $S_{\text{id}}(x)$ under the limited diversion condition of the Homogeneous reservoir with an average permeability rate $\overline{K}$ in the target segment at different positions.

④ According to the wall inflow velocity control principle, in order to make the inflow velocity distribution of the target section wall close to the ideal uniform inflow under the condition of infinite flow of the homogeneous oil reservoir, the control parameters of the target section wall surface should satisfy $\min |S_{\text{id}}(x)-S_{\text{w}}(x)|$ as much as possible.

⑤ Combining with actual engineering requirements, the genetic algorithm is used to optimize the inflow control parameters at different positions of the target segment, that is, to achieve multi-parameter optimization of the objective function $\min |S_{\text{id}}(x)-S_{\text{w}}(x)|$ at different positions.

(2) Examples Analysis

The basic parameters are shown on Table 1, the values of permeability at different locations in the 4 branch target segments are shown on Table 2. The first branch target segment penetration coefficient $T_k=k_{\text{max}}/k$ is about 2.0, the permeability differential $J_k=\frac{k_{\text{max}}}{k_{\text{min}}}$ is about 38.0; the second branch target segment penetration coefficient is about 1.5, the permeability difference is about 4.0; the third branch target segment permeability breakthrough coefficient is about 1.2, the permeability difference is about 1.5, and the 4th branch target segment permeability is 250mD. Taking the length of each branch wellbore to be 400 meters, as shown in Figure 3, the distance between the heel end of each branch target segment and the main wellbore is 20 meters.

In order to facilitate the study of the influence of the degree of heterogeneity of permeability on the results of the sub-parameter optimization of the perforation parameters at each branch target segment, only the perforation density was optimized. The optimization results are shown in Table 3. It can be seen that the inhomogeneity of the permeability along the wellbore is the main influencing factor of the perforation parameter optimization design of the target section, and the impact on the inflow profile of the target section wall is more sensitive than the wellbore pressure drop, as shown in Figure 8; the high-permeability target segment injection after optimization The hole density is small, and the perforation density of the low-penetration target segment is large, and vice versa. Thus, the inflow rate of the high-penetration target segment is reduced, the inflow velocity of the low-penetration target segment is increased, and the uniform inflow of the target segment is realized as much as possible.

| Variable name                          | Value | Variable name                          | Value |
|----------------------------------------|-------|----------------------------------------|-------|
| Supply radius (m)                      | 1000.0| Oil viscosity (mPa.s)                  | 10.0  |
| Thickness of oil layer (m)             | 10.0  | Volume factor (m$^3$/m$^3$)            | 1.15  |
| Wellbore at the bottom of the reservoir (m) | 5.0   | Pollution degree (dimensionless)       | 0.4   |
| Outer diameter of casing (m)           | 0.1778| Depth of pollution (m)                 | 0.12  |
| Casing wall thickness                  | 0.00917| Fluid density (kg/ m$^3$)              | 950   |
|                        | Wall roughness (dimensionless) | Production pressure difference (Mpa) | Perforating gun bullets |
|------------------------|--------------------------------|--------------------------------------|-------------------------|
| Target length of well (m) | 400.0                         |                                      | 102-127gun              |
| Maximum perforation density (hole/m) | 16                             |                                      | 20                      |
| Perforation depth (m)    | 0.525                         |                                      | 0.002                   |
| Perforation diameter (m) | 0.011                         | Comaption zone permeability (10⁻³μm²) | 10.0                    |

Table 2: Permeability values at different positions in each branch target segment.

| Distance from target segment to end (m) | The first branch target segment permeability value (10⁻³μm²) | The second branch target segment permeability value (10⁻³μm²) | The third branch target segment permeability value (10⁻³μm²) | The fourth branch target segment permeability value (10⁻³μm²) |
|----------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| 0                                      | 450                                                         | 300                                                         | 230                                                         | 250                                                         |
| 10                                     | 452                                                         | 300                                                         | 240                                                         | 250                                                         |
| 30                                     | 278                                                         | 257                                                         | 209                                                         | 250                                                         |
| 50                                     | 94                                                          | 215                                                         | 216                                                         | 250                                                         |
| 70                                     | 243                                                         | 347                                                         | 247                                                         | 250                                                         |
| 90                                     | 99                                                          | 175                                                         | 282                                                         | 250                                                         |
| 110                                    | 387                                                         | 206                                                         | 264                                                         | 250                                                         |
| 130                                    | 340                                                         | 242                                                         | 247                                                         | 250                                                         |
| 150                                    | 144                                                         | 247                                                         | 240                                                         | 250                                                         |
| 170                                    | 31                                                          | 228                                                         | 210                                                         | 250                                                         |
| 190                                    | 317                                                         | 316                                                         | 241                                                         | 250                                                         |
| 210                                    | 13                                                          | 372                                                         | 212                                                         | 250                                                         |
| 230                                    | 205                                                         | 252                                                         | 292                                                         | 250                                                         |
| 250                                    | 194                                                         | 381                                                         | 295                                                         | 250                                                         |
| 270                                    | 398                                                         | 235                                                         | 243                                                         | 250                                                         |
| 290                                    | 500                                                         | 131                                                         | 241                                                         | 250                                                         |
| 310                                    | 185                                                         | 359                                                         | 261                                                         | 250                                                         |
| 330                                    | 53                                                          | 104                                                         | 296                                                         | 250                                                         |
| 350                                    | 338                                                         | 231                                                         | 281                                                         | 250                                                         |
| 370                                    | 156                                                         | 119                                                         | 200                                                         | 250                                                         |
| 390                                    | 117                                                         | 252                                                         | 258                                                         | 250                                                         |
| 400                                    | 150                                                         | 100                                                         | 203                                                         | 250                                                         |

Table 3: Segmentation optimization results of perforation parameters in target segment of fishbone horizontal wells.

| Distance from target segment | Perforation type | Segmentation optimization results of perforation parameters in target segment of horizontal barb /hole.m⁻¹ |
|------------------------------|------------------|----------------------------------------------------------------------------------------------------------|
|                              |                  | ----------------------------------------------------------------------------------------------------------|

6
Figures 6, 7, 8, and 9 compare the inflow profile before and after optimization for the first set of permeability, the second set of permeability, the third set of permeability, and the average permeability, respectively. It can be seen that before the perforation parameters of horizontal wells are optimized, the inhomogeneity of permeability increases, the fluctuation of inflow velocity profiles along the horizontal wellbore fluctuates violently, the inhomogeneity of permeability decreases, the inflow velocity profile along horizontal wellbore fluctuates. Flattening; after optimizing the perforation parameters of horizontal wells, the inflow velocity in the high-permeability zone is reduced, the inflow velocity in the low-permeability zone is increased, and the inflow velocity profile of the entire horizontal wellbore approaches the ideal of the homogeneous oil reservoir to some extent. As a result the inflow velocity profile can relieve the premature rise of water in the horizontal well.

| to end (m) | Branch 1 (hole.m⁻¹) | Branch 2 (hole.m⁻¹) | Branch 3 (hole.m⁻¹) | Branch 4 (hole.m⁻¹) |
|-----------|---------------------|---------------------|---------------------|---------------------|
| 0~20      | 102-102             | 5                   | 9                   | 16                   | 15                   |
| 20~40     | 102-102             | 9                   | 13                  | 16                   | 15                   |
| 40~60     | 102-102             | 16                  | 16                  | 16                   | 15                   |
| 60~80     | 102-102             | 13                  | 7                   | 15                   | 15                   |
| 80~100    | 102-102             | 16                  | 16                  | 10                   | 15                   |
| 100~120   | 102-102             | 6                   | 16                  | 12                   | 16                   |
| 120~140   | 102-102             | 7                   | 16                  | 15                   | 16                   |
| 140~160   | 102-102             | 16                  | 15                  | 16                   | 16                   |
| 160~180   | 102-102             | 16                  | 16                  | 16                   | 16                   |
| 180~200   | 102-102             | 8                   | 8                   | 16                   | 16                   |
| 200~220   | 102-102             | 16                  | 7                   | 16                   | 16                   |
| 220~240   | 102-102             | 16                  | 14                  | 10                   | 16                   |
| 240~260   | 102-102             | 16                  | 7                   | 10                   | 16                   |
| 260~280   | 102-102             | 6                   | 16                  | 16                   | 16                   |
| 280~300   | 102-102             | 5                   | 16                  | 16                   | 16                   |
| 300~320   | 102-102             | 16                  | 7                   | 13                   | 16                   |
| 320~340   | 102-102             | 16                  | 16                  | 10                   | 16                   |
| 340~360   | 102-102             | 7                   | 16                  | 11                   | 16                   |
| 360~380   | 102-102             | 16                  | 16                  | 16                   | 16                   |
| 380~400   | 102-102             | 16                  | 14                  | 13                   | 16                   |

Figure 6: Inflow profile before and after optimizing of the first branch target segment
Figure 7: Inflow profile before and after optimizing of the second branch target segment
Figure 8: Inflow profile before and after optimizing of the third branch target segment

Figure 9: Inflow profile before and after optimizing of the fourth branch target segment

It can be seen from Table 4 that the capacity index is slightly reduced after the perforation parameters of the target segment of fishbone horizontal wells are optimized, and with the increase in heterogeneity along the permeability, the productivity index decreases after subsection optimization. But overall, the subsection optimization has no obvious effect on the productivity index of each branch target segment.

Table 4: Comparison of productivity index before and after perforation optimization in each branch target segment.

| Before and after the optimization of the capacity index comparison results | Target segment | Capacity index ($m^3$·$d^{-1}$·$MPa^{-1}$) | Loss of productivity index ($m^3$·$d^{-1}$·$MPa^{-1}$) | Percentage of the loss productivity index (%) |
|---|---|---|---|---|
| | Before Optimization | After Optimization | Before Optimization | After Optimization | Before Optimization | After Optimization | Before Optimization | After Optimization |
| Segment 1 | 26.2541 | 24.8485 | 1.4056 | 5.3538304 |
| Segment 2 | 26.2541 | 25.4893 | 0.7648 | 2.9130688 |
| Segment 3 | 26.2541 | 25.5222 | 0.7319 | 2.7877551 |
| Segment 4 | 26.2541 | 25.7212 | 0.5329 | 2.0297782 |

5. Conclusion

(1) Based on the equivalent caliper model, a coupled model of seepage and wellbore flow in the horizontal wellbore reservoir was established. Combined with the genetic optimization algorithm, a segmentation optimization method for the inflow control parameters of the target segment wall was presented, which solved the scientific optimization design problem of the fishbone horizontal wellbore perforation parameters and slotted casing parameters.

(2) The inhomogeneity of the permeability along the wellbore is the main influencing factor for the optimal design of the inflow control parameters in the target section. Also the impact on the inflow profile of the target section is more sensitive than the wellbore pressure drop.

(3) After the optimization, the permeation target area has a small perforation density, and the low permeation target section has a large perforation density. With an increase in the heterogeneity of permeability, the range of the perforation density changes, thereby reducing the inflow rate of the high permeation target section. The inflow speed of the low-penetration target segment is increased, and the maximum inflow of the target segment is achieved.

(4) After the optimization of the perforation parameters in the target segment, the capacity index decreases slightly, and as the heterogeneity of the permeability increases, the productivity index of the target segment decreases after the perforation segmentation optimization increases, but overall, the perforation parametric optimization has no obvious effect on the productivity index.
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