Dynamic Distribution Characteristics of Oil and Water during Water Flooding in a Fishbone Well with Different Branch Angles

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ABSTRACT: Lab experiments, field pilots, and numerical modeling focusing on fluid flow aspects have indicated that multi-branch wells are technically effective and promising. Several researchers have conducted some experiments for a fishbone well strategy with mixed results. Our objective in this work is to study the impact of the different fishbone well patterns, such as branch angle, on the distribution of remaining oil after water flooding. In this paper, the interference effect between branches on oil recovery is studied in three steps. First, the interferences between fishbone wells with different branch angles were measured by hydro-electric simulation experiments. Second, two-dimensional visualization water flooding experiments were carried out to clarify the remaining oil distribution at different branch angles. Third, the distribution of oil and water in fishbone wells was verified by establishing a numerical model. The modeling results agree well with the experimental phenomena. At the same time, the variation trend of water and oil production in each branch is analyzed by numerical simulation results. The results indicate that the production is strongly dependent on the branch angles, and the highest recovery was 60.2% at a 45° branch angle.

1. INTRODUCTION

At present, water flooding is still an economical and effective means to develop conventional reservoirs. However, how to efficiently improve the water flooding sweep volume and increase the drainage area is still a key problem. Compared with the conventional horizontal well, the fishbone well, with multilateral wellbores and increased reservoir drainage area, has high potential for enhancing oil production in the oilfield. Because its branches increase the contact area between the wellbore and oil formation and make it easier for oil to enter the wellbore or for fluids to be injected into the reservoir. Moreover, previous studies indicate that the fishbone well has obvious advantages in enhanced oil recovery (EOR) and wide market prospects.

The fishbone well has been approved as an effective technology for EOR of heavy oil, conventional reservoir in thin layers, and tight oil. However, the efficiency of some fishbone wells is too low to make the process economical. The reason for this is that the different structural parameters can result in significant interference and large difference in oil and water distribution. Therefore, it is of great significance to clarify the waterflooding characteristics and remaining oil distribution with different structures.

Some experimental and numerical simulation studies have been conducted to analyze the application of fishbone well in CO₂ Huff n Puff and the process of SAGD, and the recovery differences of vertical wells, horizontal wells, and multi-branch wells are compared and studied. Compared with the horizontal injection well, the fishbone well can increase the control area, form planar flooding, and hold the injection water upward slowly and evenly. Multilateral wells have better performance than vertical wells in shale due to the larger heat-exchange area during the process of in situ conversion. Zhou found that the individual layer deliverability of a multilateral well with limited sand production was three times the multilayer production of the common deviated well. Fipke and Celli discussed the concept of using fishbone wells in a heavy oil reservoir and concluded that it can be a more practical way to improve the recovery factor of intended heavy oil reservoirs. In addition, some authors studied the fishbone wells’ performance including the structural parameters of branch wells and the properties of reservoirs. Zhou et al. studied fishbone wells in an offshore oilfield and indicated that the fishbone well pattern could extend the steam distribution. Manshad found that the fishbone structure raised production by 393%, while drilling cost only increased by 130% compared with a conventional horizontal well. Al-Rbeawi and Artun described pressure distribution in the porous media by several analytical models considering

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different reservoir geometries and different multilateral horizontal wellbore configurations. Multi-branch well technology still achieves good results in coal. Multilateral horizontal wells (MLHWs) showed to perform better and have been drilled to effectively reduce the gas content of coals. Though the drilling cost of a multi-branched horizontal well (MBHW) is more higher compared to vertical wells, its high and stable productivity can compensate for the drilling cost. The parameters of the fishbone well have great influence on productivity, such as branch number, branch angle, and branch length. Numerical results indicated that the water breakthrough time had positive correlation with branch length, branch angle, and branch number. Yang et al. highlighted the importance of the optimum design for the fishbones. Lux studied the effects of branch angle and branch number on recovery. Cai found that branch number was the most important factor, whereas length of the main wellbore and length of the branched wellbore were the secondary ones. In addition, the rules and the criteria required for selection of horizontal and multilateral wells were developed. Liu proposed that fishbone wells facilitated an ideal development effect when the flow direction was perpendicular to the plane determined by the mother bore and branch. On this basis, many studies have proposed that the branch angle is an important factor causing interference between branches. For multilateral wells, the interaction among laterals can also influence productivity. The parameters related to the shape of MLHWs, such as branch length and branch angles, can obviously affect the transient pressure dynamics of MLHWs.

However, dynamic flow performances with the application of the different fishbone well patterns in water flooding have not been reported. Specifically, the influence of patterns with different branch angles on the remaining oil distribution is not clearly understood yet. In this study, hydro-electric simulation experiments were carried out to investigate the interference between branches. At the same time, the dynamic process of waterflooding and remaining oil distribution were characterized by two-dimensional visualization experiments and numerical simulations. It is proposed that branch angle has a significant impact on productivity. Finally, the variation of the remaining oil with different branch angles was analyzed, which provided suggestions for improving oil recovery by fishbone well.

2. MATERIALS AND METHODS

In order to clarify the recovery with different branch angles of fishbone well, we carried out hydropower simulation experiments to clarify the interference between different branch angles. Second, we carried out 2D visualization water flooding experiments to clarify the influence of branch angle on the distribution of remaining oil. Finally, we combined numerical model and physical simulation experiments to clarify the difference in recovery at different branch angles.

2.1. 2D Visualization Water Flooding Experiments.

2.1.1. Materials. Kerosene was used to simulate crude oil with a viscosity of 2.5 mPa s. Distilled water was used to simulate formation water for displacement. Two dyes were used in the experiments, Sudan-III (red dye) and ink (black dye). Before the flooding experiments, oil was dyed with red Sudan-III and distilled water was dyed with black ink to better distinguish them. The experimental model was filled with 120 mesh glass beads, and the whole model was homogeneous. The size of the experimental model was 60 cm × 60 cm × 2.3 cm, the permeability was about 2000 × 10⁻¹³ μm², and the porosity was about 36%. A stainless steel cylinder with a diameter of 3 mm was used to simulate fishbone wells with different branch angles (30, 45, 60, and 90°). The structural model of the fishbone well is shown in Figure 1.

![Figure 1](https://example.com/image1.png)

Figure 1. Fishbone well structure in 2D visualization experiments.

2.1.2. Experimental Process. The schematic diagram of the 2D water flooding experiment is shown in Figure 2. The experimental device is mainly composed of displacement system, 2D model, and monitoring system. Vertical wells and fishbone wells are arranged diagonally on the 2D model. The specific experimental steps are as follows:

1. Sand control: Mesh was used to wrap the perforation position on the fishbone well model to prevent some quartz sand from flowing into the main wellbore and branch wells during displacement.
2. The process of saturation: The intermediate container was filled with dyed kerosene, and the model was saturated with kerosene at 3 mL/min, which was completed when the production fluid from the oil well was continuous and without bubbles, and the injection volume and production volume were recorded at this time.
3. The process of displacement: The water flooding experiment was carried out at 3 mL/min, and the output fluid was measured with a 1000 mL measuring cylinder at the end. The time was recorded every 1000 mL of liquid produced at the output end, and the changes of oil and water distribution in the 2D model were observed during the experiment. The well was shut down when the water cut reached 98%.

2.2. Hydro-Electric Simulation Experiments. 2.2.1. Materials. The copper belt was used to simulate the reservoir supply boundary, and a Cu wire with a diameter of 1 mm was used to simulate the fishbone well model with different branching angles as shown in Figure 1. The length of the horizontal section is 40 cm, the branch shaft length is 20 cm, and the branch angles are 30, 60, and 90°, respectively. The permeability of the simulated reservoir is 496 μm², the viscosity is 30 mPa s, and the production pressure difference ΔP is 1 MPa. The model voltage was set at 11.2 V, and the conductivity of CuSO₄ solution was 496 μs/cm.

2.2.2. Experimental Process. There is a similarity between the differential equations of incompressible subsurface fluid flowing through porous media and the differential equations of charge flowing through conducting materials. There is a proportional relationship between parameters of the physical model and corresponding parameters of the prototype, which is called similarity coefficient. The similarity coefficients meet certain constraint conditions, which is called similarity criterion, as shown in eqs 1 and 2.

\[
\frac{C_p}{C_q C_r} = 1
\]
The parameters in eqs 1 and 2 satisfy the following equations.

Geometric similarity coefficient

\[ C_1 = \frac{X_m}{X_r} = \frac{Y_m}{Y_r} = \frac{Z_m}{Z_r} = \frac{L_m}{L_r} \]  

(3)

Pressure similarity coefficient

\[ C_p = \frac{\Delta U_m}{\Delta P_r} \]  

(4)

Flow similarity coefficient

\[ C_q = \frac{i_m}{I_r} = \frac{Q_m}{Q_r} \]  

(5)

Flow similarity coefficient

\[ C_p = \frac{\rho_m}{(k/\mu)_r} \]  

(6)

In the formula, subscript m represents the model and subscript r represents the reservoir. L is the geometry of the reservoir, model or well, \( L_m \), \( L_r \); \( \Delta U \) is the voltage difference, V; \( \Delta P \) is the pressure difference, MPa; \( \rho_m \) is the conductivity of the solution, \( \mu s/cm \); K is the reservoir permeability, \( 10^{-3} \mu m^2 \); \( \mu \) is the crude oil viscosity, mPa s; \( I_m \) is the electric current, mA; and \( Q_r \) is the injection rate, m\(^3\)/d.

According to the similarity theory, the shape and distribution of seepage field and electric field are similar, and they can obtain similar solutions under similar boundary conditions. Therefore, the inter-well interference experiment of the fishbone well was carried out to explore the inter-well interference and productivity difference of different branch angles. \(^{28,29}\) The experimental device is shown in Figure 3.

The specific experimental steps are as follows:

1. Model making: Copper wire with a diameter of 1 mm was used in the experiment to make fishbone well models with different branch angles.

2. Supply boundary and electrolyte solution: The size of the solution tank was about 80 cm \( \times \) 80 cm \( \times \) 20 cm. According to the tank size, a suitable copper belt was made the supply boundary, and the supply radius was set to 40 cm. With reference to the relation diagram of CuSO\(_4\) solution concentration and conductivity, the correspond-

ing CuSO\(_4\) solution was configured, and the conductivity was about 496 \( \mu s/cm \).

(3) A stable voltage of 7 V was output to the boundary and wellbore. Then, the manipulator controller program test step, test distance, test time interval, and other related parameters were set, and the test step length, test distance and test time interval were 4 cm, 80 cm, and 5 s, respectively; the program was run and the voltage was tested at different points after the value was stabilized;

(4) Data processing: Surfer software was used to draw isobars;

(5) The branch angles were changed, and the above-mentioned experimental steps were repeated.

2.3. Simulation Model. tNavigator is a state-of-the-art reservoir modeling and simulation platform, offering a wide range of advanced innovative tools for geoscience, reservoir, and production engineering disciplines. Simulation results are delivered with unlimited acceleration and scalability utilizing all GPU and CPU hardware capacity. It is reliable, easy, smart, and exhibits exceptionally high performance. In this study, the tNavigator numerical simulator was employed to simulate the process of water flooding. A 3D reservoir of 1200 m in width (I direction), 6 m in height (K direction), and 1200 m in length (J direction) was developed. The grid blocks were set equal in length (60 \( \times \) 20 m) and width (60 \( \times \) 20 m). The thicknesses of the grid blocks were 6 m with three equal zones. The reservoir was assumed to be homogeneous, and the properties of the oil used in the model are listed in Table 1. The oil used in the simulation was dead oil. The relevant parameters of the model are shown in Table 1.

The injection well (vertical well) and production well (fishbone well) were arranged diagonally along the model, respectively. The fishbone well was drilled 3 m beyond the bottom of the formation, whereas the injector well was located in the middle depth of the reservoir, as shown in Figure 4.
initial oil saturation in the model was 0.7. The reference pressure at the depth of the injection well was 30 MPa. The horizontal length of the fishbone well was 800 m with branch angles of 30, 45, 60, and 90°, respectively. The branch length was 400 m, and the branch spacing was 200 m.

3. RESULTS AND DISCUSSION

In this study, three types of experiments including hydro-electricity simulations, 2D visualization water flooding experiments, and numerical simulation experiments were carried out to study the well interference and the distribution of remaining oil with different branch angles.

3.1. Hydro-Electric Simulation Experiments. According to the hydropower simulation experiments, voltage data at different measuring points were obtained, and isobar distribution maps at different branch angles were obtained by using the Surfer software, as shown in Figure 5.

As can be seen from the Figure 5, there are significant differences in the isobars of different branch angles, but the following rules generally appear: the isobars near the wellbore are densely distributed, and the shape of isobars is close to the well type; the distribution of isobars far from the wellbore is loose, nearly elliptic, or circular, and the pressure gradient near the wellbore is large. The isobars between the branches were inward concave, which was more obvious at 45°, followed by at 30°, and the isobars were gentle at 60 and 90°, indicating that the interface of water and oil was stable at 60 and 90°. As the branch angle increases, the branch interference tends to decrease. In addition, by comparing isobars with different branch angles, it can be seen that the drainage area gradually increases with the increase of branch angles. In order to verify the difference of depletion productivity, the numerical simulation method was adopted to simulate depletion at different branch angles. The

| parameters            | physical model | numerical model |
|-----------------------|----------------|-----------------|
| size                  | 60 cm × 60 cm × 2.3 cm | 1200 m× 1200 m × 6 m |
| mean porosity         | 36%            | 36%             |
| mean permeability     | 2000 × 10⁻³ μm² | 2000 × 10⁻³ μm² |
| oil viscosity         | 2 mPa·s        | 2 mPa·s         |
| injection velocity    | 4 mL/min       | 400 m³/d        |
| horizontal length     | 40 cm          | 800 m           |
| branch length         | 20 cm          | 400 m           |
| branch angle          | 30/45/60/90°   |                 |

Figure 4. View of the well location in the reservoir model.

Figure 5. Fishbone well interference at different branch angles.
results are shown in Figure 6. Based on the oil recovery results, we can see that the recovery increases gradually in the initial stage, but the difference is small in the later stage with the increase of the branch angle. Ren et al. have finished some simulations about the MBHW with the different branch angles. Simulation results show that the structure parameters of a MBHW can be optimized to maximize its productivity, in which a branch angle from 45 to 55° is recommended.17

3.2. Dynamic Distribution Characteristics of Oil and Water. As shown in Figure 7, when the fishbone well is used as a production well, the oil and water distribution before water appearance were obtained by numerical simulation under different branch angles.

According to the distribution of streamline in Figure 7, in the case of two-branch fishbone well, there are mainly three flow zones, corresponding to horizontal well and two branches, respectively. It can be seen that the main direction of streamline gradually moved left and down with the increase of the branch angle. When the branch angle is larger, oil and water mainly advance along the transverse direction, and then, the difference of oil and water distribution appears. The difference between the longitudinal and transverse velocities decreases with the gradual increase of the branch angle. The oil saturation in the upper right corner is controlled by the main wellbore, the middle area is controlled by a branch well which is far from the producing end, and the oil saturation in the lower left corner is controlled by a branch well which is close to the producing end. At the same time, the distribution range of streamlines is larger when the branch angle is 45°. When the branch angle is 90°, there is almost no streamline distribution in the corner of the 2D visualization model and the area between the branch wells. Therefore, appropriate branch interference is beneficial to production enhancement.11 On the other hand, the large branch angle also brings great challenges to the drilling process. Therefore, the selection of a reasonable branch angle is particularly important.

Figure 8 shows the dynamic changes of water flooding with the branch angle of 30°. Through the oil–water distribution under different water cuts, the dynamic change of oil–water interface can be clearly observed. Figure 9 shows the numerical simulation results for the different water cut states in Figure 8. The physical experiments results are roughly the same as the

![Figure 6](http://pubs.acs.org/journal/acsodf) Figure 6. Recovery in depletion development of fishbone well at different branch angles.

![Figure 7](http://pubs.acs.org/journal/acsodf) Figure 7. Changes in oil saturation at different branch angles before water breakthrough.

![Figure 8](http://pubs.acs.org/journal/acsodf)
numerical simulation results for different water cuts. The water first flows into the branch well closer to the injection well.

As shown by the marker in Figure 9, on comparing the distribution of oil saturation at the early stage of water breakthrough, the same saturation interval is narrow in the direction parallel to the main wellbore; in the direction perpendicular to the main wellbore, the same oil saturation range is wider. This is mainly because more water is flowing perpendicular to the main wellbore; at the stage of high water cut, the gradient of oil saturation in the horizontal is smaller than that in the vertical, mainly because the dominant channel is formed after water breakthrough and the remaining oil in the vertical is less. After water breakthrough in each branch well, the water flows along the wellbore.

We statistically analyzed the oil and water production of 30° branch angle based on the production data of each perforation point in the numerical simulation. As described in Figure 10, the main branch produces the most oil with the increase in volume of injected water. At the same time, branch 2 produces the most water. Injection water flows preferentially into branch 2, and then, the water production rate of branch 2 is higher and rises rapidly, and the oil production decreases rapidly. Comparing the daily production rates of different branches, the main branch has a relatively long stable production period because it has a later time to see water and a smaller decreasing rate of daily oil production. The water appearance time of branch 1 is almost the same as that of branch 2, and water breaks through a little earlier in branch 1. The water production rate is almost consistent with the water appearance time. The earlier the branch water appearance time is, the higher the water production rate will be in the subsequent production process. This is mainly due to the formation of dominant flow channels. Therefore, the water production mainly comes from the branch 2 which is closer to

![Figure 8. Process of 2D visualization water flooding with 30° branch angle.](image)

![Figure 9. Oil saturation at different water cuts (30° branch angle).](image)
the injection wells, and unequal branch length will help to prolong water appearance time. The contributions of oil production from the main branch, branch 1, and branch 2 are 39.6, 32.72, and 27.68%, respectively, and so, the main branch and branch 1 are the main oil-producing branches.

3.3. Variation Characteristics of Water Cut. Figure 11 shows the relationship between water cut and injection in 2D visualization water flooding experiment with different fishbone well branch angles.

As shown in Figure 11, the breakthrough time of fishbone wells with different branch angles is different in the process of water flooding, and the water appearance time of 45° is earlier, followed by 60 and 30°, and the water appearance time of 90° branch angle is the last. However, when the branch angle is 90°, the water cut rises faster than the others after water breakthrough.

Based on the numerical simulation results, we obtained the change trend of oil−water ratio during the water flooding process, as shown in Figure 12. There is no oil−water ratio before water breakthrough. However, when water breaks through, most of the produced fluid is still oil, and so, the oil−water ratio is usually high. Then, with the gradual increase of the water cut, the oil−water ratio decreases gradually and finally approaches zero. The change of oil−water ratio is mainly divided into three stages, the stage of rapid decrease of oil−water ratio, the stage of slow decrease, and the stage of stability. The results show that water appears first in the wellbore when the branch angles are 45 and 60°, followed by 30 and 90°. By comparing the water appearance time in Figures 11 and 12, it can be found that the water appearance time in fishbone wells with different branch angles is roughly the same. The oil−water ratio rises rapidly in different angles of fishbone wells after water breakthrough. When the branch angle is 45°, the oil−water ratio increases the least. This indicates that the branch angle of 45° is relatively stable in the process of displacement.

3.4. Recovery and Distribution Characteristics of Remaining Oil. Figure 13 shows the remaining oil distribution after water flooding with different branching angles. The straight well was arranged in the lower right corner for water injection, and the fishbone well was arranged horizontally in the upper left corner.
As shown in Figure 13, there is less residual oil remaining on the side of the fishbone well at 45°, while more residual oil exists between the branching wells at the 90° branch angle. The residual oil is mainly distributed on the left side and the corner of the 2D model, and the results are basically similar to the residual oil distribution of the numerical simulation in Figure 16. The small amount of residual oil distribution on the right side of the model in Figure 13 is mainly due to the fact that the straight well is not located in the lower right corner of the margin.

Figure 14 shows recovery about the physical simulation experiments. We found that recovery first increased and then decreased with the increase of branch angle. The recovery at 45° branch angle was higher than that at any other branch angle in the experiments. The water breakthrough time is late, but the water cut increases rapidly after water breakthrough when the branch angle is 90°, as shown in Figure 11. At the same time, it can be seen from Figure 14 that the recovery factor at the 90°
branch angle is higher than that at other branch angles before water breakthrough, but the increase of recovery slows down sharply after water breakthrough. At the same time, there is more residual oil between the main wellbore and branch 2 when the branch angle is 90°, as shown in Figure 13. Therefore, the recovery at 90° was lower than that at 45 and 60°. In the initial production period, the flow rate increases significantly as the branch angle increases, and the branch angle has an important effect on the recovery in fishbone wells. Figure 16 shows the distribution of oil saturation with different branch angles when the water cut is 90%. Compared with the horizontal well in Figure 15, the fishbone well is more efficient, and the residual oil between the branches gradually increases with the increase of branch angle.

4. CONCLUSIONS
Combining 2D visualization water drive experiments and numerical simulations, the paper investigates the oil—water transport characteristics and residual oil distribution during the development of fishbone wells with different branch angles. Moreover, the interference between branches of fishbone wells with different branching angles was clarified through hydro-electric simulation experiments. In addition, the water and oil production variation characteristics and contribution share of each branch well were analyzed. The results of the study provide important theoretical support for the optimization of the branch parameters of the fishbone wells at a later stage. Three conclusions can be drawn from this study.

First, the hydro-electric simulation experiments show that the drainage area gradually increases as the branch angle of the fishbone well increases, but the interference between branches appears to gradually decrease and then stabilize. As the interference between branches increases, the recovery of depletion gradually decreases.

Second, by combining 2D model water flooding experiments and numerical simulations, fishbone wells with 45° branch angle are recommended because they have the longest production time and a relatively high recovery. The remaining oil is mainly distributed in the model corners and inter-branch locations.

Third, the branch closer to the injection well produces much more water than the other branches, while the horizontal main branch has a longer stable production period and higher oil production, and so, later studies should focus on optimizing the length matching relationship between the main branch and other branches to achieve optimal production.

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Notes
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