Numerical Simulation of Oil -Water Flow Velocity Field and Flow Pattern in Horizontal Wells and Near Horizontal Wells

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Abstract. Oil-water flow widely exists in oilfield development. Due to the gravity differentiation, the oil-water flow in low-flow horizontal wells has a clear characteristics of stratified flow. With the increase of flow rate, the stratified characteristics are not obvious, which leads to the difficulty of multiphase flow phase separation flow interpretation in oilfield. In this paper, the oil-water flow in horizontal wells is taken as the research object. The VOF model of Fluent software is used to study the relationship between velocity field and flow pattern distribution characteristics with water cut, well deviation angle and total flow. The results show that with the increase of water cut, the oil-water separation level gradually moves up, and the velocity of water phase is greater than that of oil phase. When the well deviation angle changes slightly, the flow stratification of oil-water changes sharply, and the flow velocity in the pipeline also changes. When the total flow rate is lower than 200 m³/d, the oil-water phases have obvious stratified flow characteristics. With the increase of flow rate, the oil-water interface fluctuates. The average velocity of oil and water is not much different.

1. Introduction

In the 1980s, the development and application of horizontal well technology in the world has entered a new stage. The technical level has been significantly improved and the cost has been greatly reduced. It has become one of the main technical means for the development of oil and gas reservoirs. Velocity measurement in the detection of horizontal well flow parameters is an extremely important research content. The accurate measurement of velocity can be used to analyze the output of each perforated zone in the well and provide a basis for the establishment of a multiphase flow interpretation model. Since the gravity direction perpendicular to the well axis, the horizontal section oil-water phase and velocity by the vertical well as a symmetrical field distribution becomes asymmetrical distribution, which makes it difficult to interpret production logging data. Therefore, it is necessary to study the characteristics of oil-water flow velocity field in horizontal wells. On the basis of summarizing the previous research results, Trallero⁶ carried out the experimental study of oil-water flow in a small-diameter low-flow horizontal tube. The oil-water flow in the horizontal tube was divided into stratified flow (oil and water have a clear interface) and dispersed flow (one phase of the fluid dispersed into another phase of the continuous fluid as droplets). The stratified flow usually occurs when the total flow is low, while the dispersed phase usually occurs when the total flow is high. When the total flow rate is medium, the mixing mode of these two flow patterns may appear. Due to the complex downhole environment, there are three kinds of fluid flow stages. When the well deviation angle is 90°, the density of oil is smaller at the top, and the density of water is larger at the bottom. Since the viscosity of oil is greater than that of water, the friction that hinders the flow is generated, and the velocity of oil is slightly lower than that of water. When the well deviation angle is greater than 90°, the oil
gathers at the top of the pipeline, and the buoyancy of oil drags the water at the bottom to flow upward, and the speed of the oil is greater than that of the water. When the well deviation angle is less than 90°, because the density of water is greater than that of oil, the downward flow rate of water is greater than that of oil. For low-flow horizontal wells, the flow pattern is mainly stratified flow. As the total flow rate gradually increases, the oil-water flow interface is disturbed. The oil-water flow velocity changes with the change of water cut and well deviation angle, which makes it very difficult to interpret fractional flow of multiphase flow. In this paper, the flow state of oil and water in horizontal wells is the research object. The VOF multiphase flow model of Fluent software is used to numerically simulate the oil-water flow under different water cut, well deviation angle and total flow rate are studied. The variation characteristics of velocity field are analyzed, which provides the basis for the interpretation of production logging data.

2. Establishment of Oil-water Two Phase Numerical Simulation Model for Horizontal Well

According to the tubing or casing string of oil wells produced in the oil field and the multiphase flow simulation experiment device of Yangtze University Production Logging Center, in order to make the numerical simulation can be compared with the oil wells and the experimental situation, this paper selected a section of pipeline with a length of 20 m and a diameter of 124 mm as the research object. The Design Modeler is used to establish the three-dimensional geometric model and mesh the pipeline. The sweep method is used to generate 1000 units on the side. All the grid types of the circular surface are triangular free surface grid types, as shown in Figure 1.

![Figure 1. The grid division model of horizontal.](image)

The fluid in the pipeline is tap water and industrial white oil. The viscosity of white oil is 0.00292 kg / m·s and the density is 826.3 kg / m³. The density of water is 998.2 kg / m³ and the viscosity is 0.001003 kg / m·s. Numerical simulation total flow range is 100 ~ 600 m³/d, flow design point is 100, 200, 300, 400, 600 m³/d. The range of water cut is 20 ~ 80 %, with 20 % as the step length, and the water cut of 50 % is selected for comparison. The variation range of well deviation angle is 85° – 95°, and the well deviation angles are 85°, 87°, 93°, 95°. Boundary conditions are set. The right end of the pipeline is the inlet of the oil-water mixture, and is set as the velocity inlet boundary condition, which is suitable for incompressible fluid. The pipeline is 20 m long, and it can be considered that the outlet is a fully developed flow, and is set as outflow. In order to ensure the smooth progress of the simulation, the obtained results are accurate and feasible. In the whole simulation process, the control variables are only assumed to be points, ignoring the influence of condensate gas escaped from crude oil in the gathering and transportation process, and the influence of temperature change on the viscosity and density of crude oil and water. At the same time, the pipeline wall is also identified as a non-slip wall.

3. Numerical Simulation

3.1. VOF Multiphase Flow Model

The continuity equation as equation (1) shows:

$$\nabla \cdot \vec{u} = 0$$  (1)

Momentum equation as equation (2) shows:

$$\frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \nabla \vec{u} = -\nabla p + \rho \vec{g} + \nabla \cdot \mu (\nabla \vec{u} + \nabla^T \vec{u}) + \vec{f}$$  (2)

The VOF model phase equation as equation (3) shows:
\[
\frac{\partial \rho}{\partial t} + \rho \mathbf{v} \cdot \nabla \alpha = 0
\]  

In the formula, \( \rho \) is the fluid density (kg/m³). \( t \) is time (s). \( \mathbf{v} \) is velocity vector (m/s). \( \mu \) is dynamic viscosity (kg/m·s). \( f \) is surface tension (N/m³).

3.2. Turbulence Model k-\( \varepsilon \) Model

Turbulent pulsating kinetic energy equation (4):

\[
\rho \frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k \mathbf{u}_i) = \frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j}\right) + C_{1k} \frac{\varepsilon}{k} (G_k + G_b - Y_M + S_k) \\
\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon \mathbf{u}_i) = \frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon} \frac{k}{\varepsilon} (G_k + G_b - C_{3k} \varepsilon) - C_{2\varepsilon} \rho \frac{k^2}{\varepsilon} + S_\varepsilon
\]

Formula: \( \rho \) is fluid density (kg/m³). \( k \) is turbulent kinetic energy (J). \( \mu_t \) and \( \mu_e \) are average speed. \( \sigma_k \) and \( \sigma_\varepsilon \) are the turbulent Prandtl number of \( k \) equation and \( \varepsilon \) equation respectively. \( G_k \) is the generation term of turbulent kinetic energy caused by the average velocity gradient. \( G_b \) is term for the generation of turbulent kinetic energy caused by buoyancy. \( Y_M \) is contributed to pulse expansion in compressible turbulence. \( \varepsilon \) is turbulent dissipation rate (%). \( \mu \) is turbulent viscosity (Pa·s). \( t \) is time (s). \( X_i \) and \( X_j \) is space coordinates. \( C_{1k} = 1.44, C_{2k} = 1.92, C_{3k} = 1 \) are all empirical constants.

This paper mainly studies the flow pattern and velocity field of oil-water flow in long circular tube. VOF method can be used to deal with the problem of complex free surface, can only use a function to represent the free surface of various complex changes, can effectively capture the interface between oil and water movement, where the turbulence model selection k-\( \varepsilon \) model, given the ‘turbulence intensity’ and ‘hydraulic diameter’. Since the Reynolds number of each working condition is calculated to know that the flow under each simulation condition is in the stratified flow state, the stratified flow model is set in Fluent.

4. Numerical Simulation Results and Analysis

4.1 Variation of Oil-water two-phase Flow and Velocity Field in Horizontal Wells under Different Water Cuts

The total flow rate of simulation is 100 m³/d, and the inlet water cut changes from 20% to 80%. The water cut difference of each working condition is 20%. At the same time, the working condition with water cut of 50% is selected to carry out the numerical simulation of flow pattern and velocity field under different water cut conditions. The distribution maps of oil-water two-phase flow and velocity field under different water cut are shown in Figures 2 – 6.

Figure 2. When the total flow of oil and water is 100 m³/day, the water cut is 20%, and the well deviation is 90°, the horizontal well flow pattern distribution and velocity field distribution map.

1) As shown in Figure 2, when the water cut is 20%, it can be seen from the cross section that the water holdup is greater than 20%. According to the velocity field, it can be seen that the average velocity of the lower water phase is higher than that of the upper oil phase, the high value area of the velocity field is in the lower part of the pipeline.
When the total flow of oil and water is 100 m³/day, the water cut is 40%, and the well deviation is 90°, the horizontal well flow pattern distribution map and velocity field distribution map.

2) As shown in Figure 3, when the water cut is 40%, it can be seen from the cross section that the water holdup is less than 40%, and the water cut is greater than the water holdup. According to the velocity field, it can be seen that the average velocity of the lower water phase is higher than that of the upper oil phase. The high value area of the velocity field is in the lower part of the pipeline.

When the total flow of oil and water is 100 m³/day, the water cut is 50%, and the well deviation is 90°, the horizontal well flow pattern distribution map and velocity field distribution map.

3) As shown in Figure 4, it can be seen from the cross section that when the water cut is 50%, the oil and water in the wellbore account for half each. According to the velocity field, it can be seen that the average velocity of the lower water phase is higher than that of the upper oil phase, and the high value range of the velocity field becomes larger.

When the total flow of oil and water is 100 m³/day, the water cut is 60%, and the well deviation is 90°, the horizontal well flow pattern distribution map and velocity field distribution map.

4) As shown in Figure 5, when the water cut is 60%, it can be seen from the cross section that the water holdup is less than 60%. According to the velocity field, it can be seen that the average velocity of the lower water phase is higher than that of the upper oil phase. The high value area of the velocity field begins to move gradually to the top of the pipeline.
5) As shown in Figure 6, when the water cut is 80%, the water in the wellbore accounts for the majority. It can be seen from the cross section that the water holdup is less than 80%. According to the velocity field, it can be seen that the average velocity of the lower water phase is higher than that of the upper oil phase. The high value area of the velocity field is in the lower water phase.

With the increase of water cut, the oil-water flow tends to be stable over time after passing through the inlet section. When the water cut is 50%, it is stratified flow due to the small initial inlet velocity, and the viscous force plays a major role. Under the action of viscous force, the velocity of water is slightly lower than that of oil, and the water holdup is slightly higher than the oil holdup.

4.2 Variation of Oil-water two-phase Flow and Velocity Field in Near Horizontal Wells under Different Well Deviation Angles

Due to the uneven distribution of each phase fluid in horizontal wells and low angle inclined wellbores, the oil-water flow structure is also very sensitive to wellbore inclination, so the influence of different inclination on the flow pattern is explored. The Fluent software is used to simulate the pipeline with the total flow rate of 100 m³/d, the water cut of 60% and the well inclination of 85°, 87°, 93°, 95°. The distribution maps of oil-water two-phase flow and velocity field under different well deviation angles are shown in Figure 7-10.

Figure 7. When the total flow of oil and water is 100 m³/day, the water cut is 60%, and the well deviation is 85°, the horizontal well flow pattern distribution map and velocity field distribution map.

Figure 8. When the total flow of oil and water is 100 m³/day, the water cut is 60%, and the well deviation is 87°, the horizontal well flow pattern distribution map and velocity field distribution map.
1) As shown in Figure 7-8, it can be seen from the flow pattern that the water holdup is greater than 60%, and the water cut is less than the water holdup. According to the velocity field, the velocity field of oil-water flow is symmetrically distributed. The average velocity of oil phase at the top is greater than that of water phase at the bottom. The high value area of velocity is distributed at the top of the pipeline section.

Figure 9. When the total flow of oil and water is 100 m³/day, the water cut is 60%, and the well deviation is 93°, the horizontal well flow pattern distribution map and velocity field distribution map.

5) As shown in Figure 9-10, it can be seen from the cross section of the flow pattern that the water holdup is less than 60%. According to the velocity field, the oil-water flow velocity field is symmetrical distribution, and the high velocity area is distributed at the bottom of section. Due to the small initial velocity, the phase interface is a slightly mixed laminar flow and laminar flow. In the uphill stage, the velocity of the upper oil phase is greater than that of the lower water phase. Compared with the horizontal, the water holdup is greater than the oil holdup, and this phenomenon is more obvious with the increase of well deviation angle. However, in the downhill stage, due to the density difference, gravity plays a leading role, resulting in the average velocity of water phase being greater than that of oil phase.

4.3 Variation of Oil-water two-phase Flow and Velocity Field in Horizontal Wells under Different Flow Rates

Since the flow pattern and velocity field distribution in the two-phase pipe changed with the change of flow rate, the total flow rates of 100 ~ 600 m³/d were selected for the numerical simulation. The distribution maps of oil-water two-phase flow and velocity field with different total flow rates are shown in Figure 11 – 15.

Figure 11. When the total flow of oil and water is 100 m³/day, the water cut is 50%, and the well deviation is 90°, the horizontal well flow pattern distribution map and velocity field distribution map.
When the total flow of oil and water is 200 m³/day, the water cut is 50%, and the well deviation is
90°, the horizontal well flow pattern distribution map and velocity field distribution map.

When the total flow of oil and water is 300 m³/day, the water cut is 50%, and the well deviation is
90°, the horizontal well flow pattern distribution map and velocity field distribution map.

When the total flow of oil and water is 400 m³/day, the water cut is 50%, and the well deviation is
90°, the horizontal well flow pattern distribution map and velocity field distribution map.

Flow pattern and velocity field distribution of horizontal wells with total flow rate of 600 m³/d
and water cut of 50 % at well deviation angle 90°.

From the figure, it can be concluded that the viscous force plays a major role when the flow rate of is 100
m³/d at well deviation angle 90°. When the flow rate is 200 m³/d, the viscous effect gradually weakens due to
the increase of flow rate and begins to be less than the influence of turbulence on the flow pattern of oil-
water flow. At the entrance section, the ‘turbulence’ effect is more obvious. When the steady state is reached,
the length of the entrance increases, and the interface between oil and water is not stable. When the velocity reaches 300 m³/d, the effect of turbulence is further enhanced. When the velocity reaches 400 m³/d, the turbulence is enhanced to disturb a small part of water to the top of the pipeline, and the oil phase is dispersed to the upper part of the pipeline. When the velocity reaches 600 m³/d, the oil-water flows in a long part of the pipe, and the oil-water flow at the outlet is stratified flow. As the total flow of oil and water increases, the high-speed center area of the velocity field in the tube gradually shifts to the center, and the high-speed center area basically coincides with the center at 600 m³/d, and the velocity field is axisymmetric.

5. Conclusions and Understanding
In this paper, VOF model in Fluent software is used for numerical simulation of oil-water flow in horizontal wells under different water cut, well deviation angle and total flow rate. The results show that:
(1) When the well deviation angle and water cut are constant, the oil-water two-phase flow is a stratified flow with a clear interface at low flow rate. As the total flow of oil and water increases, the oil-water flow interface is disturbed. The high speed center area of velocity field in pipe gradually shifts to the center of pipe, and the velocity field changes from asymmetric distribution to symmetric distribution.
(2) When well deviation and total flow remain unchanged, the flow pattern is stratified flow at low flow rate, and the velocity of lower water phase is greater than that of upper oil phase. As the water cut increases, the high-speed center area of velocity field gradually shifts to the upper part of the pipeline.
(3) When the water cut and total flow rate are constant, the upper oil phase velocity is greater than the lower water phase in the uphill stage, the high speed area of velocity field is mainly distributed in the oil phase. In the downhill stage, due to the density difference, the circulation flow of oil is easy to occur. The high-speed region of the velocity field is mainly distributed in the water phase, and the velocity field is axisymmetric.
(4) Fluent software can simulate the oil-water flow flow in horizontal wells. The numerical simulation results of this paper have certain guiding significance for the development of field array flow imaging production logging instruments and data interpretation, but it needs to be adjusted to conform to the experimental results.

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