Numerical Investigation on Gas Accumulation and Gas Migration in Enlarged Boreholes of Horizontal Gas Wells

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Abstract. The horizontal section of the horizontal gas well will form a horizontally enlarged borehole due to factors such as the collapse of the well wall, and it is easy to form gas accumulation in the enlarged section, which will cause accidents such as overflow. Therefore, it is very important to study the gas accumulation law in the horizontal enlarged section. Based on the actual horizontal wellbore size, a three-dimensional horizontal rectangular-enlarged borehole model and a three-dimensional horizontal curved-enlarged borehole model are established in this paper to simulate the phenomenon of gas clustering in the enlarged diameter section. The research results show that, under the same length of the enlarged section, the gas discharge of the horizontally rectangular-enlarged borehole is difficult, which is more likely to cause gas accumulation, but the horizontally curved-enlarged borehole is less likely to cause gas accumulation; When the fluid flows through the horizontal enlarged diameter section, the pressure will increase and the pressure flowing out of the expansion section will decrease, and the faster the flow velocity, the greater the pressure in the expanding section.

Keywords: Horizontal gas well; Enlarged borehole; Gas accumulation; Gas migration; Numerical simulation.

1. Introduction

As horizontal well drilling technology becomes more and more mature, horizontal well drilling technology has become the main research direction in the field of oil and gas wells in the world (Dai et al, 2019. Zhao et al, 2012. Ma et al, 2014.). Horizontal well drilling technology which can increase oil and gas production, increase oil and gas recovery, and save oil and gas development investment, has been widely implemented in more than 70 countries (Wang et al, 2014. Bai et al, 2014. Wan et al, 2011.). The main reason for the rapid development of horizontal well drilling technology is that this technology can bring significant economic benefits. Statistics on a large number of construction cases show that the investment cost of conventional horizontal wells only accounts for half of the investment cost of ordinary vertical wells, but the output is three to five times or more than that of vertical wells. (Liu et al, 2018. Gao et al, 2018. Vefring et al, 1995.)

Under the action of drilling fluid erosion, the horizontal section of a horizontal well may expand in diameter due to blockage and collapse of the well wall during the drilling process. The gas carried by the drilling fluid is obstructed by the horizontal expansion section and the gas recirculation effect causes the gas to accumulate in the horizontal expansion section and cannot be discharged in time, causing kick, stopping the pump, and reducing the drilling time. Therefore, it is necessary to establish the basic mathematical model of horizontal wellbore flow and to study the law of gas accumulation and flow in the horizontal expansion section through numerical simulation, and then propose a gas discharge method.
2. Physical Model and Governing Equation

2.1. Physical Model

The diameter of the horizontally expanded borehole is 0.2159m, and the gas accumulates on the top of the expanded borehole. The schematic diagram of gas accumulation in the horizontally expanded borehole is shown in Figure 1.

Establishing a reasonable three-dimensional physical model of a horizontally expanded borehole according to the actual situation is the key to simulating the gas accumulation and discharge laws of a horizontally expanded borehole. To reduce the amount of calculation and improve simulation efficiency, only the fluid domain is established. The borehole diameter is 0.2159m, and the horizontal sections on both sides of the model are equal to 1m. Physical models of horizontal boreholes with different expanded diameter shapes are established, as shown in Figure 2.
Use ICEM CFD software for grid division, using a structured grid. According to the characteristics of fluid movement, the wall grid is locally densified to ensure accurate simulation of gas-liquid two-phase characteristics. (Wang et al, 2005. Yu, 2008. Morsi et al, 2002. Li et al, 2013) The grid division is shown in Figure 3.

2.2. Governing Equation
This article mainly studies the motion relationship between gas and liquid, without considering the energy conversion relationship between the two. Through the numerical analysis method, it can be simulated to get a result that is more consistent with the actual situation. In this paper, considering the gravity factor, the VOF model, and the RNG k-ε turbulence model are selected to simulate the flow changes under different working conditions. The governing equation is established as follows:

- Continuity equation:

\[
\frac{\partial}{\partial t}(\alpha_g \rho_g) + \nabla \cdot (\alpha_g \rho_g \mathbf{v}_g) = 0
\]

(1)

\[
\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l \mathbf{v}_l) = 0
\]

(2)

\[
\alpha_g + \alpha_l = 1
\]

(3)

- Momentum equation:

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \left[ \mu \left( \nabla \mathbf{v} + \nabla \mathbf{v}^T \right) \right] + \rho \mathbf{g} + \mathbf{F}
\]

(4)

- Turbulence equation:
  Turbulent energy equation k:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k \mathbf{v}_l)}{\partial x_j} = \frac{\partial}{\partial x_j}(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}) + G_k + \rho \varepsilon
\]

(5)

Dissipation rate equation ε:

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon \mathbf{v}_l)}{\partial x_j} = \frac{\partial}{\partial x_j}(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}) + \frac{C'_\varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}
\]

(6)

Where: \( \mathbf{v} \) is the fluid velocity, m/s; \( x_i, x_j \) are the space coordinate; \( \mathbf{g} \) is the acceleration of gravity, m/s^2; \( \rho \) is the fluid density, kg/m^3; \( \mu \) is the fluid viscosity, Pa·s; \( \mu_{eff} \) is the effective fluid viscosity, Pa·s; \( \mathbf{F} \) is Volume force, N; \( t \) is time, s; \( k \) is turbulent kinetic energy, J; \( \varepsilon \) is turbulent energy dissipation; \( G_k, C_{2\varepsilon}, C'_\varepsilon, \alpha_k, \alpha_\varepsilon \) are constants.

2.3. Physical Parameters
Gas-liquid density and dynamic viscosity are shown in Table 1.

|                  | Density (kg·m⁻³) | Dynamic viscosity (Pa·s) |
|------------------|------------------|--------------------------|
| Test solution    | 997.0            | 9.028×10⁻⁴               |
| Air              | 1.185            | 1.86×10⁻⁵                |
2.4. Determination of Simulation Methods and Conditions

2.4.1. Equation discretization and solving method. This paper chooses the unsteady state, implicit separation algorithm. The finite volume method is used to discretize the control equations and select an appropriate discretization format. The pressure interpolation format chooses the full-strength weighting format; the density, momentum, turbulent kinetic energy, turbulent dissipation rate, and energy interpolation format choose the first-order upside style with high stability and fast calculation speed, and the volume fraction interpolation format chooses the geometric reconstruction format, pressure-Speed coupling algorithm selection PISO algorithm. (Chen, 2009. Pan et al, 2019. Zhou, 2019.)

2.4.2. The setting of definite solution conditions. The definite solution condition is composed of boundary conditions and initial conditions.

- Inlet conditions: Adopt the velocity inlet boundary conditions, set the inlet velocities to 0.8m/s, 1 m/s, 1.2m/s, and increase the numerical simulation analysis at different speeds according to the simulation conditions. Set the inflow gas volume fraction to 0. The method of turbulence definition selects hydraulic diameter and turbulence intensity.
- Outlet conditions: Adopt the pressure outlet boundary conditions, turbulence definition method to choose the hydraulic diameter and turbulence intensity.
- Initial conditions: Consider the influence of gravity, set \( \gamma = -9.81 \text{m/s}^2 \) under the fluent environment panel. In the initialization panel, select the inlet to initialize, and then in the Patch panel to partially repair the initial gas volume fraction to achieve the initial gas accumulation height setting in the model. Set to record a gas-liquid composition cloud image every 100-time steps, and animation can be formed after the simulation is completed to observe the flow pattern.

2.4.3. Convergence conditions. In FLUENT software, the residual error is used to represent the convergence of the calculation. If the residuals of each equation meet the set criteria, the calculation process will be terminated. In this question, the residuals in every equation are all set as \( 1.0 \times 10^{-4} \), the time step length is selected as 0.001s, the step length of maximum iteration is selected as 20, and the total time step is set as 10,000 at the beginning, and then increased according to the specific flow field.

3. Simulation Results and Analysis

3.1. Flow Field Analysis

3.1.1. Analysis of flow field in the rectangular expanded borehole. To facilitate observation and analysis, the model composition diagram is simplified into a two-dimensional phase diagram. The circulating medium annulus flows from left to right, the direction is positive; otherwise, it is the reverse direction.
Figure 4. (a) Composition diagram of the horizontal rectangular enlarged diameter section (When velocity=1m/s) (b) Composition diagram of the horizontal rectangular enlarged diameter section (When velocity=2.4m/s) (c) Composition diagram of the horizontal rectangular enlarged diameter section (When velocity=2.8m/s).

Table 2. Exhaust conditions at different speeds.

| Velocity (m/s) | 1.0  | 1.2  | 1.4  | 1.6  | 1.8  | 2.0  |
|---------------|------|------|------|------|------|------|
| Gas remaining state | Not exhausted | Not exhausted | Not exhausted | Not exhausted | Not exhausted | Not exhausted |
| Velocity (m/s) | 2.2  | 2.1  | 2.6  | 2.8  | 3.0  | 3.2  |
| Gas remaining state | Not exhausted | Not exhausted | Not exhausted | Not exhausted | Almost exhausted | Completely drained |

It can be seen from Figure 4 that as the velocity increases, the amount of gas accumulation in the horizontal rectangular expansion section gradually decreases, and the gas is concentrated on the top of the expansion section. By analyzing the velocity vector diagrams at various speeds, it is found that the lower part of the gathering gas is driven by the gas to generate a positive velocity, and the upper part of the gathering gas is a velocity in the opposite direction, thus keeping the gas in balance and gathering at the top of the expansion section. Through multiple sets of simulations, the simulation results are shown in Table 2. When the inlet velocity is 3.2m/s, it is the critical exhaust velocity, and the gas in the horizontal rectangular expansion section can be completely discharged.

3.1.2. Analysis of flow field in the curved borehole. To facilitate observation and analysis, the model composition diagram is simplified into a two-dimensional phase diagram. The circulating medium annulus flows from left to right, the direction is positive; otherwise, it is the reverse direction.
It can be seen from Figure 5 that as the velocity increases, the amount of gas accumulation in the horizontal curved expansion section gradually decreases, and the gas is concentrated on the top of the expansion section. When the velocity is 0.2m/s, there is a phenomenon of gas accumulation, and the gas cannot be discharged from the expanded diameter section. When the velocity is greater than 0.2m/s, there is no gas accumulation in the horizontal curved diameter expansion section.

3.2. Pressure Analysis
- Pressure analysis of rectangular expanded borehole

Figure 5. (a) Composition diagram of the horizontal curved enlarged diameter section (When velocity=0.2m/s) (b) Composition diagram of the horizontal curved enlarged diameter section (When velocity=0.4m/s) (c) Composition diagram of the horizontal curved enlarged diameter section (When velocity=0.8m/s).
Figure 6. (a) Pressure diagram of the horizontally enlarged rectangular diameter section (When velocity=1m/s) (b) Pressure diagram of the horizontally enlarged rectangular diameter section (When velocity=2.4m/s) (c) Pressure diagram of the horizontal enlarged rectangular diameter section (When velocity=2.8m/s).

- Pressure analysis of curved expanded borehole
Figure 7. (a) Pressure diagram of the horizontal curved enlarged diameter section (When velocity=0.2m/s) (b) Pressure diagram of the horizontal curved enlarged diameter section (When velocity=0.4m/s) (c) Pressure diagram of the horizontal curved enlarged diameter section (When velocity=0.8m/s).

It can be seen from Figure 6 and Figure 7 that the pressure in the rectangular expansion section and the curved expansion section is greater than the normal horizontal sections on both sides, and as the velocity increases, the pressure in the expansion section is greater. When there is a gas accumulation in the expansion section, the gas pressure at the top of the expansion section is greater than the liquid pressure at the lower end of the gas.

4. Conclusion
According to the research in this article, the article has the following conclusions:
• Based on the establishment of the continuity equation, kinetic energy equation, and turbulence equation, this paper carried out numerical simulation and obtained gas pressure and flow velocity cloud diagrams of horizontally expanded boreholes.
• In the case of the same length of the expansion section, if the gas in the horizontal rectangular expansion borehole needs to be completely exhausted, the speed must be greater than 3.2m/s. However, in the horizontally curved expansion section of the wellbore, the complete exhaust velocity only needs to be greater than 0.2m/s. Therefore, it is difficult to discharge gas from a horizontal rectangular expanded borehole, which is more likely to cause gas accumulation, while a horizontal curved expanded borehole is less likely to cause gas accumulation.
• When the fluid passes through the horizontal expansion section, the pressure will increase, and then the pressure will drop when flowing out of the expansion section. And as the speed increases, the pressure in the expansion section increases.
• Numerical simulation method reveals the gas accumulation and discharge law of horizontal gas well expanded borehole, which provides ideas for avoiding safety hazards caused by gas accumulation in engineering.
• This article only uses numerical simulation methods. Although the simulation results conform to objective laws, it is still necessary to carry out experimental demonstrations in the next step.

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