Flow Characteristics of UBD Applied to Gas Reservoirs

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Abstract. Underbalanced drilling technology implemented in high pressure and low permeability gas reservoirs can better protect gas formation from drilling fluid damage, and can improve the drilling speed, but gas invade into the wellbore from the formation by the underbalanced pressure will make the borehole flow presented two-phase flow state. The gas phase compactness and slippage effect will increase the drilling of well control difficulty. In order to ensure the invaded gas is not appear violent slippage and rapid inflation, study the two-phase flow law is necessary to determine the size of the applied well backpressure, applying process of gas distribution law in borehole, and the bottom hole pressure, for the reasonable design of drilling fluid density, well backpressure design and the equipment selection. This paper applies the numerical difference method to two-phase flow one-dimensional equations were solved. Combined with an example of drilling, the gas void fraction distribution, migration and bottom-hole pressure change law is given, which provides theoretical basis for low permeability gas reservoirs in underbalanced pressure drilling borehole designing.

1. Introduction

In order to avoid formation damage caused by conventional drilling during the development of high-pressure and low-permeability gas reservoirs, underbalanced drilling technology can be used to ensure that the gas reservoir is not contaminated by drilling fluid, better maintain the original permeability of the gas reservoir, and improve gas reservoir production effectiveness. Although the permeability of the gas field is lower, the higher the formation pressure, the faster the gas production growth rate. When underbalanced drilling is performed in a gas reservoir, more gas will still invade the wellbore. If the wellhead back pressure is not properly controlled, the gas will quickly move up to the wellhead due to compressibility and slippage effects. Therefore, it is necessary to perform wellbore gas-liquid two-phase flow calculation and wellhead back pressure design before underbalanced drilling to further guide the drilling fluid density design and wellhead equipment selection. In this paper, combined with the underbalanced drilling project design for development wells in the Kelameili gas field in Xinjiang, the relevant analysis and calculation of the flow law of underbalanced drilling in high pressure and low permeability gas reservoirs are carried out.

2. Gas production while drilling for UBD in high-pressure and low-permeability gas reservoirs

The exponential productivity equation for gas wells [1]:

\[ q_i = C(p_r^2 - p_b^2)\eta = C(p_r + p_b)^\eta(p_r - p_b)\eta \]  

(1)
Where $q_g$---Gas production, m³/d; $C$---Gas production coefficient, m³/d.MPa$^{2n}$; $p_i$, $p_f$---Formation pressure. Buttonhole pressure, MPa; $n$---Gas production index, Dimensionless. The value range is 0.5–1.

According to the SY/T6543.1-2008 "Technical Specification for Underbalanced Drilling: Liquid Phase", with regard to the principles of selection of fractured and natural gas reservoir under pressure values, the dynamic pressure difference of underbalanced drilling is selected as MPa, for high pressure formations, the bottom hole pressure and formation pressure during underbalanced drilling are close to each other, so the formula (1) can be expressed as:

$$q_g \approx C \rho_p^n (2 \Delta p)^n \leq C (3 \rho_p^n)^n$$  \hspace{1cm} (2)

According to the productivity equation of a gas well, it can be seen that the productivity of high-pressure and low-permeability gas layers is very significantly affected by formation pressure. The higher the formation pressure, the faster the gas production growth rate. According to the oil and gas productivity test of Karamay drilling, the natural gas production while drilling under underbalanced conditions is predicted to be 3.88×10^4 m³/d.

3. Annular air-liquid two-phase flow theory

3.1. Basic equation of gas-liquid two-phase one-dimensional flow

Due to the compressibility of the gas and the slippage effect between the gas and liquid phases, the gas-liquid flow parameters in the annulus are constantly changing along the flow direction. When studying the gas-liquid two-phase flow in the annulus, the following assumptions are made for water-based drilling fluids: (1) The dissolution of natural gas is not considered; (2) The heat transfer process between the fluid in the wellbore and the formation is already in equilibrium; (3) Treat cuttings and drilling fluid as one phase-liquid phase. The one-dimensional flow model along the shaft axis [2-4] is:

The continuity equation is:

$$\frac{\partial}{\partial t} [\rho_m (1 - \lambda)] + \frac{\partial}{\partial z} [\rho_m v_m (1 - \lambda)] = 0$$ \hspace{1cm} (3)

$$\frac{\partial}{\partial t} [\rho_g \lambda] + \frac{\partial}{\partial z} [\rho_g v_g \lambda] = 0$$ \hspace{1cm} (4)

The momentum equation is:

$$\frac{\partial}{\partial t} [\rho_m v_m (1 - \lambda) + \rho_g v_g \lambda] + \frac{\partial}{\partial z} [\rho_m v_m^2 (1 - \lambda) + \rho_g v_g^2 \lambda] + \frac{\partial p}{\partial z} + \left[ \frac{\partial}{\partial z} \right] + [\rho_m (1 - \lambda) + \rho_g \lambda] = 0$$ \hspace{1cm} (5)

Empirical model of gas phase velocity:

$$v_g = K_g \left[ v_m (1 - \lambda) + v_g \lambda \right] + v_{gs} \left( \rho_g, \rho_m, \lambda, \sigma, d_e, d_i \right)$$ \hspace{1cm} (6)

Where, Kg=1.0 (bubbly flow), or 1.2 (slug flow).

Gas-liquid two-phase equation of state:

$$\rho_m = \rho_m (T, p)$$ \hspace{1cm} (7)

$$\rho_g = \rho_g (T, p)$$ \hspace{1cm} (8)

Gas slippage speed:

When the bubbly flow is dispersed($0 < \lambda < 0.25$):

$$v_{gs} = 0.25 \left[ \frac{\rho_m^2 \sigma g}{\rho_m - \rho_g} \right]^{0.25}$$ \hspace{1cm} (9)

When fully developed slug flow($\lambda > \lambda_{gs}$):

$$v_{gs} = 0.55 K_g \left[ \frac{(d_e + d_i) (\rho_m - \rho_g)}{\rho_m} \right]^{0.5}$$ \hspace{1cm} (10)
The slip velocity of the transitional flow state is the linear interpolation of the slip velocity of bubbly flow and slug flow.

Where, \( t \)---time, \( s \); \( \lambda \)--Gas void ratio, dimensionless; \( p \)-- pressure, MPa; \( \rho_{m}/\rho_{g} \)-- Density of liquid and gas phase, \( \text{kg/m}^3 \); \( v_{m}/v_{g} \)-- Liquid and gas velocity m/s; \( z \)--Well deep, m; Subscript \( f \)--Friction term; \( g \)--Acceleration of gravity ,m/s\(^2\); \( K_{f} \)--Gas slip coefficient, Dimensionless; \( \sigma \)--Surface Tension, \( \text{N/m} \); \( d/d_{d} \)--Wellbore inner diameter, drill string outer diameter, m; \( T \)--temperature, K; \( v_{gs} \)--Bubble slip speed, m/s; \( \gamma_{p} \)--Liquid phase yield value, Pa; \( \mu_{p} \)--Liquid phase plastic viscosity, Pa.s; \( N_{R} \)--Reynolds number, dimensionless; Subscript gs--Slug flow; \( v_{b} \)--Slug flow return velocity in annulus, m/s.

3.2. Numerical solution of pressure distribution
Take \( t = t + \Delta t, z = z + \Delta z \), divide the wellbore into a one-dimensional grid, and obtain the difference format of the liquid-phase continuity equation:

\[
(1 - \alpha)[v_{m} \rho_{m} (1 - \lambda) ]_{z+}^{+} + \alpha v_{m} \rho_{m} (1 - \lambda) ]_{z+}^{+} - (1 - \alpha)[v_{m} \rho_{m} (1 - \lambda) ]_{z}^{+} - \alpha v_{m} \rho_{m} (1 - \lambda) ]_{z}^{+} + \alpha[v_{m} \rho_{m} (1 - \lambda) ]_{z}^{+} + \alpha[v_{m} \rho_{m} (1 - \lambda) ]_{z}^{+} = \frac{\Delta z}{2 \Delta t}[\rho_{m} (1 - \lambda) ]_{z+}^{+} + \rho_{m} (1 - \lambda) ]_{z+}^{+} - \frac{\Delta z}{2 \Delta t}[\rho_{m} (1 - \lambda) ]_{z}^{+} + \rho_{m} (1 - \lambda) ]_{z}^{+},
\]

(11)

The difference format of the gas continuity equation:

\[
(1 - \alpha)[v_{g} \rho_{g} \lambda ]_{z+}^{+} + \alpha v_{g} \rho_{g} \lambda ]_{z+}^{+} - (1 - \alpha)[v_{g} \rho_{g} \lambda ]_{z}^{+} + \alpha v_{g} \rho_{g} \lambda ]_{z}^{+} = \frac{\Delta z}{2 \Delta t}(\rho_{g} \lambda )_{z+}^{+} + (\rho_{g} \lambda )_{z+}^{+} - \frac{\Delta z}{2 \Delta t}(\rho_{g} \lambda )_{z}^{+} + (\rho_{g} \lambda )_{z}^{+},
\]

(12)

The difference format of the mixture momentum equation:

\[
[v_{m} \rho_{m} (1 - \lambda) ]_{z}^{+} + v_{g} \rho_{g} g \lambda_{z}^{+} + \alpha[v_{m} \rho_{m} (1 - \lambda) ]_{z}^{+} + v_{g} \rho_{g} g \lambda_{z}^{+}]_{z}^{+} / 2 - [v_{m} \rho_{m} (1 - \lambda) ]_{z}^{+} + v_{g} \rho_{g} g \lambda_{z}^{+}]_{z}^{+} / 2 + (1 - \beta)(p)_{z+}^{+} + \beta(p)_{z+}^{+} = \frac{\Delta z}{4} \left[ \frac{\Delta p}{\Delta z} \right] _{z+}^{+} + \frac{\Delta p}{\Delta z} \right] _{z+}^{+} \right] _{f}^{+} ^{+} \right] _{f}^{+}
\]

(13)

where, \( \alpha, \beta \)--accelerated iteration factors of quality and pressure parameters

The initial boundary conditions can be solved by equations (2) ~ (7), in which mud pump displacement, riser pressure, bottom hole pressure, wellhead back pressure, and wellhead return flow must be known in advance.

4. Wellhead back pressure and gas migration in the annulus

In order to better illustrate the effect of wellhead back pressure on suppressing gas expansion and bottom hole pressure reduction, and to demonstrate the important influence of gas invasion, gas expansion and migration in the wellbore on well control safety, specific calculation examples are combined for analysis.

4.1. Known parameters

Casing inner diameter 244.5mm, casing depth 2000m; drill bit diameter 215.9mm, drilled to 3500m; drill collar diameter 159mm, drill pipe diameter 127mm; mud pump displacement 26L/s, drilling fluid
density 1.6 g/cm³, plastic viscosity. It is 0.03 Pa.s; the temperature gradient is 3°C/100m; the gas invasion velocity of the bottom hole formation is 1L/s, and the relative density of natural gas is 0.6.

4.2. Simulation and analysis of gas migration law in the annulus

When 1m³ gas was invaded in the annulus, the wellhead back pressure value and the gas migration law in the annulus were simulated. It should be noted that since it is not actual construction, only the influence of different wellhead back pressure on gas expansion is studied here, so it is not considered whether the formation is balanced after the wellhead is pressurized.

![Figure 1. Gas distribution in the annulus when gas moves upward for 10 min](image1)

![Figure 2. Annular air distribution when gas moves upward for 20 minutes](image2)

From the analysis in Fig. 1 and Fig. 2, it can be seen that when natural gas in the bottom hole formation just invades the wellbore, the gas is in the bottom hole high pressure and high temperature state, the expansion is not obvious, and it has been in a bubbly flow or dispersed bubbly flow state for a certain distance at the bottom as shown in Figure 1, the relationship between the volumetric gas content of gas and the wellhead back pressure is not very close. In the range of back pressure from 0.1MPa to 6MPa, the gas volumetric gas content is about 3%. The amount of expansion changes very little. At the same time, the slip velocity of gas in the liquid is very small and it moves upwards almost
synchronously with the drilling fluid. As shown in Figure 1, under different wellhead back pressure conditions, the length of the well section and the depth of the well where the gas moves upward is almost the same.

However, with the rapid upward movement of gas in the annulus, the wellbore pressure and temperature continue to decrease, the gas volume continues to expand, and the equivalent density of drilling fluid in the annulus continues to decrease, causing the bottom hole pressure to continue to decrease, especially when the gas migrates near the wellhead. The gas content will change drastically at the time, which will cause the overflow to develop rapidly near the wellhead. It can be seen from Figure 2 that the wellhead back pressure has a very obvious effect on suppressing gas expansion.

5. Conclusion
(1) During the implementation of underbalanced drilling in low-permeability gas reservoirs, the intrusion and upward migration of gas in the annulus presents a gas-liquid two-phase flow. Due to the compressibility of the gas and the slippage effect between the gas and liquid phases, the flow parameters are along the flow direction. Adopting the basic equation of one-dimensional flow of gas-liquid two-phase flow, discretizing and numerically solving it in the space domain and time domain, can well show the gas migration and change law in the annulus.

(2) The volumetric gas content of gas decreases with the increase of wellhead back pressure. In the early stage of gas invasion, the gas is strongly affected by the bottom-hole high pressure, and the wellhead back pressure has no obvious inhibitory effect on the gas volume expansion and upward migration velocity, but in the later stage of the gas invasion, the suppression effect on the gas invasion expansion and migration velocity is significant. The application of wellhead back pressure can well restrain the expansion and migration speed of gas at the wellhead. This special advantage is more suitable for well control construction of gas wells, especially wells containing acid gas.

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