

Analysis of Factors Influencing Overflow in Changqing Advanced Water Injection Areas

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Abstract: Changqing Oilfield is a typical "three-low" (low permeability, low pressure, low productivity) unconventional reservoir. Advanced water injection development leads to abnormal reconstruction of reservoir pressure, forming a narrow density safety window, which results in frequent overflow and great difficulty in disposal. To accurately identify the core targets for overflow prevention and control, this study focuses on "numerical model solving". First, the rheological law of drilling fluid is determined through experiments (providing input parameters for the model), and then a coupled numerical model of water invasion-annular pressure is established. By solving with finite difference discretization, the influences and coupling mechanisms of key factors such as reservoir open thickness, permeability, drilling fluid density, and displacement on overflow are systematically analyzed: the smaller the drilling fluid density, the slower the growth of water invasion flow rate; the larger the reservoir open thickness and the higher the permeability, the greater the water invasion flow rate; when the drilling fluid displacement increases, migration acceleration dominates the water invasion increment, and the water invasion rate grows faster at high displacement. The results of this study provide theoretical support for overflow risk prediction and refined prevention and control in Changqing advanced water injection areas, and also offer references for drilling safety guarantee in similar water injection areas.

Keywords: Advanced Water Injection Area; Narrow Density Window; Drilling Fluid Rheology; Annular Pressure Loss.

1. Introduction

Due to the particularity of the "three-low" reservoirs in Changqing Oilfield and the frequent overflow and water production hazards caused by advanced water injection development, the contradiction between overflow and leakage is prominent. Current research on overflow in water injection areas has achieved certain progress. Liu Xiaoli et al. [1] pointed out that reservoir pressure reconstruction and narrow density window are the core geological backgrounds for frequent overflow. Their research clarified the transformation effect of advanced water injection on the reservoir pressure field, but did not involve the pressure response law during drilling; Song Yagang et al. [2] analyzed the pressure distribution characteristics of low-permeability reservoirs after advanced water injection through physical simulation experiments, but failed to establish a quantitative correlation between the pressure field and water invasion rate; Cui Xianglong et al. [3] qualitatively analyzed the regulatory effects of drilling fluid density and displacement on overflow. Although they clarified the correlation trend between each factor and overflow, they lacked an in-depth characterization of the "water invasion-temperature-pressure" coupling mechanism, making it difficult to quantify the interaction intensity between factors; He Miao et al. [4] compared the influences of different rheological models on the calculation accuracy of wellbore pressure and pointed out that the three-parameter model is more suitable for high-temperature and high-pressure environments, but did not carry out verification analysis coupled with water invasion; Qu Xianwei [5] established a hydraulic parameter calculation model for managed pressure drilling, and Yan Ronghui et al. [6] explored real-time calculation methods. Although these provide mathematical models for wellbore pressure

calculation, most existing models adopt simplified assumptions to ignore transient coupling effects, resulting in calculation accuracy that is difficult to meet on-site requirements.

In view of the geological characteristics of Changqing advanced water injection areas and the difficulties in handling overflow and water production hazards, this study focuses on different temperature, pressure, and overflow conditions. By analyzing the influence laws of temperature and pressure on drilling fluid performance, a prediction model for drilling fluid rheological parameters under different downhole conditions is determined. Furthermore, a calculation model for string and annular pressure, as well as pressure loss of drill bits and downhole power drilling tools is established. The model accuracy is verified with field data, ultimately providing technical support for wellbore cleaning, hydraulic parameter calculation, and downhole pressure closed-loop monitoring and dynamic control.

2. Determination of Drilling Fluid Rheological Properties and Establishment of Rheological Model

The selection of rheological models and prediction of rheological parameters directly affect the description of fluid movement behavior, thereby determining the accuracy of wellbore pressure calculation [7]. To explore the differences between calculated values of rheological parameter models and measured values within the on-site temperature and pressure range, this study conducts on-site drilling fluid rheological performance tests to determine its rheological model.

(1) Experimental System

An OFITE high-temperature and high-pressure rotational

viscometer is used in the experiment to measure the shear stress of three types of drilling fluids at shear rates of 600 r/min, 300 r/min, 200 r/min, 100 r/min, 6 r/min, and 3 r/min under conditions of temperature 23-100°C and pressure 10-40 MPa; the aging experiment is conducted at 100°C for 16 h using a high-temperature and high-pressure aging tank. The drilling fluids used in the experiment are three commonly used systems on-site, with specific formulas as follows:

1) Low-solid-phase polymer system (System 1): The density of this system is 1.10 g/cm³, consisting of 0.1%-0.2% viscosity-increasing agent, 1%-2% high-temperature and salt-resistant fluid loss agent, 1%-2% modified asphalt, 0.3%-0.5% low-viscosity polyanionic cellulose, 2%-3% acid-soluble reservoir protection agent, 5%-8% KCl, and NaOH.

2) Strong inhibition and strong plugging drilling fluid system (System 2): The density of this system is 1.23 g/cm³, composed of 0.3%-0.5% low-viscosity polyanionic cellulose, 3%-4% modified asphalt, 3%-4% high-temperature and salt-resistant fluid loss agent, 3%-4% acid-soluble reservoir protection agent, 0.1%-0.2% viscosity-increasing agent, 0.2%-0.3% NaOH, 8%-10% KCl, and barite.

3) Micro-nano strong plugging drilling fluid system (System 3): The density of this system is 1.43 g/cm³, including 5% fluorescence-free asphalt-like material, 3% polymer compound, 2%-3% high-temperature and salt-resistant fluid loss agent, 3% acid-soluble reservoir protection agent, 3% anti-collapse agent, 0.1%-0.2% viscosity-increasing agent, 0.2%-0.3% NaOH, 30% weighting agent, 15% saturated solution, and barite.

(2) Drilling Fluid Rheological Performance Test

The rheological curves of the three drilling fluids under different temperature and pressure conditions are shown in Figures 2.1-2.3. It can be seen from the figures that with the increase of shear rate, the shear stress of the three drilling fluids increases to varying degrees under different temperatures and pressures; at the same temperature, the shear stress has a weak positive correlation with pressure; at the same pressure, the shear stress has a significant negative correlation with temperature; at high shear rates, the shear stress is more affected by temperature and pressure.

Whether the rheological parameters can be applied to wellbore pressure calculation mainly depends on whether the drilling fluid rheological model can characterize the measured rheological experimental data under different temperature and pressure conditions with high fit. According to the measured values, the rheological characteristics of the drilling fluids used in the experiment are more in line with the three-parameter Herschel-Bulkley rheological model (yield stress τ_c , consistency coefficient K , flow behavior index n):

$$\tau = \tau_c + K\gamma^n \quad (1)$$

Where: τ is shear stress, Pa; γ is shear rate, s⁻¹; τ_c is yield stress, Pa; K is consistency coefficient, Pa·s ^{n} ; n is flow behavior index.

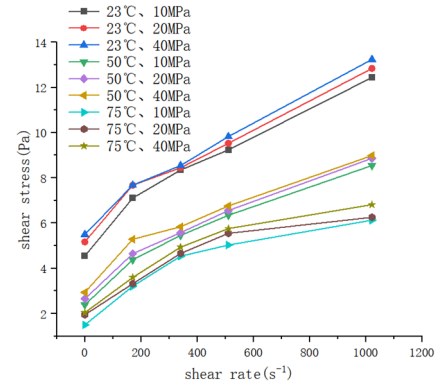
The average relative error between each rheological parameter and the experimental measured values under different temperature and pressure conditions is only 2.43%, which can meet the engineering calculation requirements.

(3) Establishment of Drilling Fluid Rheological Model

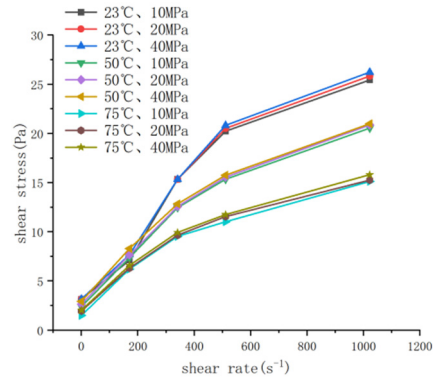
In Section 2.2, the rheological parameters of the Herschel-Bulkley model under three densities, temperatures, and pressures have been obtained. In this section, based on the existing rheological parameter data, temperature (T) and pressure (P) are taken as independent variables, and rheological parameters are taken as dependent variables. The

empirical formulas for predicting the rheological parameters of drilling fluids with a certain density are respectively regressed, and the influence laws of temperature and pressure on each rheological parameter are analyzed:

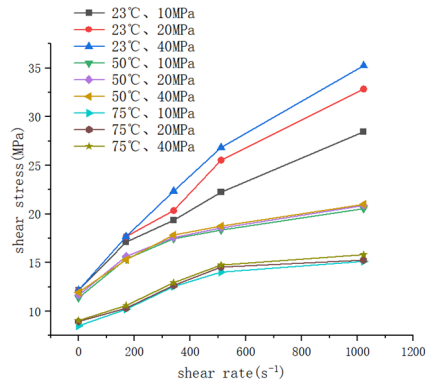
$$\tau_c = f(T, P) \quad (2)$$



(a) System 1, density 1.10 g/cm³



(b) System 2, density 1.23 g/cm³



(c) System 3, density 1.43 g/cm³

Figure 1. Drilling fluid performance curves

$$n = f(T, P) \quad (3)$$

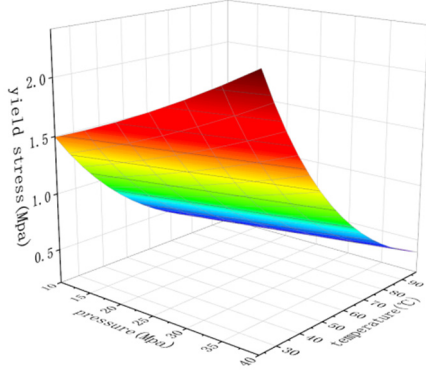
$$K = f(T, P) \quad (4)$$

Among them, the regression function can be described by the form:

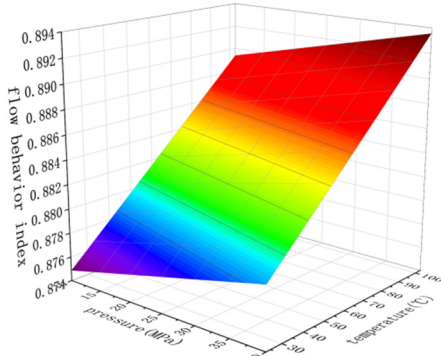
$$\mu = \mu_0 e^{\alpha(T-T_0) + \beta(P-P_0)} \quad (5)$$

Where α and β are undetermined coefficients, which can be obtained by multiple linear regression; T_0 and P_0 are reference temperature and pressure; μ_0 is the drilling fluid viscosity corresponding to the reference temperature and pressure. In this paper, the minimum experimental temperature and pressure are taken as the reference, and multiple linear regression is performed on the drilling fluid of System 1 (density 1.1 g/cm³). The prediction models of yield stress, flow behavior index, and consistency coefficient under

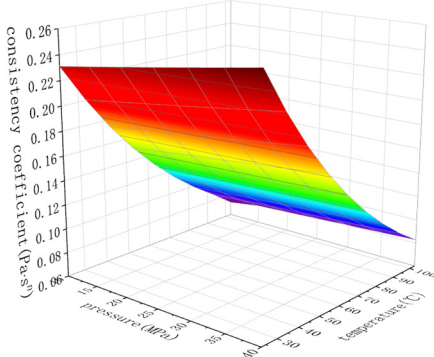
different temperature and pressure conditions are shown in Figure 2.



(a) Variation of Herschel-Bulkley yield stress τ with temperature and pressure



(b) Variation of Herschel-Bulkley flow behavior index n with temperature and pressure



(c) Variation of Herschel-Bulkley consistency coefficient K with temperature and pressure

Figure 2. Rheological characteristics of System 1 drilling fluid

3. Analysis of Water Invasion Wellbore Annular Pressure

During the conventional managed pressure drilling in Changqing advanced water injection areas, the reservoir pressure forms a narrow density safety window after reconstruction by advanced water injection. When the bottom hole pressure is lower than the pressure of the water injection layer, the formation injected water is prone to invade the wellbore. Due to the differences in physical properties such as density and viscosity between formation injected water and drilling fluid, the invasion of formation injected water into the wellbore (referred to as water invasion) will change the composition and mechanical properties of the fluid in the wellbore, thereby causing dynamic changes in annular pressure. The fluctuation of annular pressure in turn affects

the water invasion rate, forming a strong coupled transient process. This not only aggravates the overflow risk but also increases the difficulty of bottom hole pressure regulation [8].

Based on the established drilling fluid rheological parameter prediction model, by analyzing the influence law of injected water invasion on drilling fluid performance, a wellbore annular pressure calculation model under water invasion conditions is established to determine the influences of drilling fluid density, reservoir parameters, drilling process parameters, etc., on water invasion rate and annular pressure [9]-[12].

(1) Establishment of Water Invasion Wellbore Pressure Model

The model is established based on the following assumptions: (a) The fluid in the wellbore is one-dimensional unsteady flow; (b) After water invades the wellbore, it mixes uniformly with the drilling fluid instantaneously and can be regarded as homogeneous flow; (c) The invasion of cuttings and gas is not considered. The following control equations are established.

Mass conservation equations are respectively established for the drilling fluid phase and the water phase. Continuity equation of drilling fluid:

$$\frac{\partial}{\partial z}(\rho_d u_d E_d A) + \frac{\partial}{\partial t}(\rho_d u_d E_d A) = 0 \quad (6)$$

Continuity equation of water:

$$\frac{\partial}{\partial z}(\rho_s u_s E_s A) + \frac{\partial}{\partial t}(\rho_s u_s E_s A) = q_s \quad (7)$$

and water density, respectively, kg/m^3 ; E_d and E_s are volume fractions of drilling fluid and water, dimensionless; A is cross-sectional area of the control volume, m^2 ; q_s is the mass of invading water per unit time and unit thickness, $\text{kg}/(\text{s} \cdot \text{m})$. When the control volume is in the non-water invasion section, q_s is zero.

Momentum equation of the mixture of drilling fluid and groundwater:

$$\frac{\partial(\rho_d u_d^2 E_d A + \rho_s u_s^2 E_s A)}{\partial z} + \frac{\partial(\rho_d u_d E_d A + \rho_s u_s E_s A)}{\partial t} + \frac{d(AP)}{dz} + (\rho_d E_d + \rho_s E_s)gA + A\left(\frac{dP}{dz}\right)_f = 0 \quad (8)$$

Where: $A\left(\frac{dP}{dz}\right)_f$ is the friction per unit well depth between the mixture of groundwater and drilling fluid and the wall; u_d and u_s are the flow velocities of drilling fluid and water, respectively, m/s .

When drilling through the water injection section, the formation pressure is greater than the bottom hole pressure, and groundwater invades the wellbore. According to Darcy's seepage formula, the water productivity prediction equation (water seepage equation) is derived:

$$Q_s = \frac{K_s A}{\mu_s L} (P_p - P_{bh}) \quad (9)$$

Where: Q_s is water invasion volume flow rate, cm^3/s ; K_s is water permeability, μm^2 ; A is the contact area between the wellbore and the water injection layer, cm^2 ; μ_s is water viscosity, $\text{Pa} \cdot \text{s}$; P_p is formation pressure, Pa ; P_{bh} is bottom hole pressure, Pa ; L is the length of the seepage path, cm .

The velocity equation of the mixture of groundwater and drilling fluid can be described as:

$$u_{\text{mix}} = E_d u_d + E_s u_s \quad (10)$$

Where: E_d and E_s are volume fractions of drilling fluid and water, dimensionless; u_d and u_s are flow velocities of drilling fluid and water, respectively, m/s . They can be described by the following equations:

$$E_d = \frac{Q_d}{Q_d + Q_s} \quad (11)$$

$$E_s = \frac{Q_s}{Q_d + Q_s} \quad (12)$$

Where: Q_s is water invasion volume flow rate, cm^3/s ; Q_d is drilling fluid volume flow rate, cm^3/s .

At this time, the Reynolds number in the wellbore can be expressed as:

$$\text{Re} = \frac{d_H u_{\text{mix}} \rho_{\text{mix}}}{\mu_{\text{mix}}} \quad (13)$$

When $\text{Re} \leq 2000$, the flow is laminar:

$$f = \frac{24}{\text{Re}} \quad (14)$$

When $\text{Re} > 2000$, the flow is turbulent:

When $\varepsilon/d < 0.004$, it is a smooth pipe, and the friction coefficient in the pipe is:

$$\frac{1}{\sqrt{f}} = 4 \log \text{Re} \sqrt{f} - 0.394 \quad (15)$$

When $\varepsilon/d \geq 0.004$, it is a rough pipe, and the friction coefficient in the pipe is:

$$\frac{1}{\sqrt{f}} = -4 \log \left(\frac{1.255}{\text{Re} \sqrt{f}} + \frac{\varepsilon}{3.7 d_H} \right) \quad (16)$$

At this time, the annular friction pressure drop in the pipe can be expressed as:

$$\left(\frac{dp}{dz} \right)_f = \frac{f u_{\text{mix}}^2 \rho_{\text{mix}}}{2 d_H} \quad (17)$$

Where: d_H is the hydraulic radius of the wellbore annulus, m; u_{mix} is the flow velocity of the mixed fluid of drilling fluid and water, m/s; ρ_{mix} is the density of the mixed fluid, kg/m^3 ; μ_{mix} is the plastic viscosity of the mixed fluid, $\text{Pa} \cdot \text{m}$; Re is Reynolds number, dimensionless; ε is the roughness of the annular string, m; f is friction coefficient, dimensionless; $\left(\frac{dp}{dz} \right)_f$ is annular friction pressure drop, Pa/m .

(2) Initial and Boundary Conditions and Model Solution

Initial condition: At the initial moment ($t=0$), no water invasion has occurred, the fluid inside the entire wellbore is single-phase drilling fluid, and the drilling fluid is in a stable flow state at this time.

Boundary conditions: At the bottom hole position ($z=H$), the total flow rate of drilling fluid is the sum of the base flow rate and the time-varying additional flow rate at the bottom hole position; at the wellhead position ($z=0$), the pressure of drilling fluid is equal to the time-varying wellhead control pressure.

Based on the conservation of mass and energy, the basic control equations of wellbore two-phase flow are established, and a wellbore multiphase flow model for the wellbore overflow process is established. The finite difference method is adopted to divide the space and time into equal-step grids. By discretizing the control equations, the grid node parameters are solved sequentially, and the iteration is performed until the overflow reaches a stable state.

(3) Discretization Processing

Under drilling conditions, when water invades the formation, the drilling fluid and water mix uniformly and flow to the wellhead, so the slip effect between drilling fluid and water does not need to be considered, and the space step can be selected as an equal step.

Space step:

$$Z = \frac{H}{N} \quad (18)$$

Time step:

$$\Delta t = \frac{Z}{u_s} \quad (19)$$

1) Numericalization of the equations

Momentum equation of the mixture:

$$\frac{\partial(\rho_d u_d^2 E_d A + \rho_s u_s^2 E_s A)}{\partial z} + \frac{\partial(\rho_d u_d E_d A + \rho_s u_s E_s A)}{\partial t} + \frac{d(AP)}{dz}$$

$$+ (\rho_d E_d + \rho_s E_s) g A + A \left(\frac{dp}{dz} \right)_f = 0 \quad (20)$$

2) Wellbore grid division:

The partial differential equation of the transient model of the wellbore in the water injection layer can be expressed as:

$$\frac{\partial X}{\partial t} + \frac{\partial Y}{\partial z} = 0 \quad (21)$$

The time derivative of the equation is replaced by the central difference formula:

$$\left(\frac{\partial X}{\partial t} \right)_{i,n} = \frac{X_i^{n+1} - X_i^{n-1}}{2 \Delta t} \quad (22)$$

The derivative of the equation in the z direction is replaced by the forward difference formula:

$$\left(\frac{\partial Y}{\partial z} \right)_{i,n} = \frac{Y_i^{n+1} - Y_i^{n-1}}{\Delta z} \quad (23)$$

Then the transient partial differential equation can be expressed as:

$$\frac{X_i^{n+1} - X_i^{n-1}}{2 \Delta t} + \frac{Y_i^{n+1} - Y_i^{n-1}}{\Delta z} = 0 \quad (24)$$

Difference equation of the momentum equation of the mixed fluid:

$$\frac{(\rho_d u_d E_d A + \rho_s u_s E_s A)_i^{n+1} - (\rho_d u_d E_d A + \rho_s u_s E_s A)_i^{n-1}}{2 \Delta t} + \frac{(AP)_{i+1}^n - (AP)_i^n}{\Delta z} + \frac{1}{2} \left[(\rho_d E_d g A + \rho_s E_s A)_{i+1}^n + (\rho_d E_d g A + \rho_s E_s A)_i^n \right] + \frac{1}{2} \left[\left(A \left(\frac{dp}{dz} \right)_f \right)_{i+1}^n + \left(A \left(\frac{dp}{dz} \right)_f \right)_i^n \right] = 0 \quad (25)$$

3) Solution of the numerical model

Taking the pressure at each node of the wellbore when there is no overflow as the initial condition, the water phase distribution state at the next moment is calculated according to the initial wellbore pressure, and then the flow velocity is calculated according to the known parameters and phase distribution, and finally the pressure at the next moment is calculated until the wellhead. Compare the calculated wellhead pressure with the actual wellhead pressure to see if it meets the accuracy requirements. If not, correct it and recalculate.

The specific calculation steps are as follows:

(a) Determine the wellbore geometric dimensions, known parameters of drilling fluid, etc.;

(b) Determine the initial conditions, that is, the temperature, pressure, density, flow velocity and other parameters at each node of the wellbore when no overflow occurs;

(c) Calculate the water invasion amount according to the initial moment pressure P_i^0 ;

(d) Calculate the water phase distribution $(E_i^1)_s$ at the next moment according to the water invasion amount and the definition of phase distribution;

(e) Substitute the given parameters and phase volume fraction into the difference equation of the continuity equation to obtain the water phase velocity $(u_i^1)_s$ and the drilling fluid velocity $(u_i^1)_d$;

(f) Substitute $(u_i^1)_s$, $(u_i^1)_d$ and $(E_i^1)_s$ into the difference equation of the momentum equation to obtain the pressure P_i^1 ;

(g) With the obtained pressure P_i^1 , repeat steps (c)-(f) until the overflow reaches a stable state, and finally obtain the entire grid pressure distribution.

4. Case Analysis

To verify the effectiveness and accuracy of the constructed coupled numerical model of water invasion-pressure-temperature, verification analysis is carried out based on the

on-site drilling data of Gao X Well in Changqing advanced water injection area. The influence laws of drilling fluid density, formation open thickness, reservoir permeability, and drilling fluid displacement on water invasion rate are systematically explored, providing a basis for the optimization of overflow prevention and control parameters.

(1) Basic Model Parameters

The second spudding of Gao X Well has developed pore fractures, a narrow safe density window, and a high-pressure water layer. The on-site drilling parameters are as follows: water viscosity 0.5 mPa·s, permeability 100 md, open water injection layer thickness 15 m, high-pressure water layer pressure coefficient 2.58, overflow depth 3560 m, drilling fluid density 1.28-1.43 g/cm³, drilling fluid displacement 30 L/s, geothermal gradient 2.1°C/100 m, drill string combination: Φ241.3 mm drill bit + Φ127 mm drill pipe. Based on the above parameters, the variation law of bottom hole pressure with time and the evolution characteristics of water invasion rate under different conditions are obtained through model calculation. The calculation results are shown in Figures 4.1-4.5.

(2) Model Verification

It can be seen from Figure 3 that after water invasion occurs, the bottom hole pressure shows a phased characteristic of first slowly decreasing and then rapidly decreasing: in the initial stage (0-30 min), the volume of invading water is small, only distributed in the local area near the bottom hole, and the impact on the overall pressure field of the wellbore is limited, so the decreasing rate of bottom hole pressure is gentle; with the continuous water invasion (after 30 min), the water body gradually migrates upward in the annulus, accounting for an increasing proportion of the annulus space. The decrease in the density of the mixed fluid leads to the weakening of the supporting effect on the bottom hole pressure. At the same time, the increase in water invasion rate further aggravates the pressure drop, making the bottom hole pressure enter a rapid decreasing stage until the overflow is stable. This evolution law is consistent with the trend of pressure monitoring data during the actual on-site overflow process, verifying the accuracy of the model.

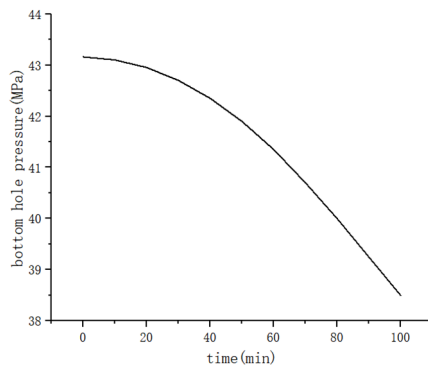


Figure 3. Variation of bottom hole pressure with time

(3) Influence Laws of Various Factors on Water Invasion Rate

1) Influence of Drilling Fluid Density on Water Invasion Rate

It can be seen from Figure 4 that drilling fluid density has a significant regulatory effect on the growth trend of water invasion rate: the smaller the density, the slower the growth of water invasion flow rate. When the drilling fluid density of 1.43 g/cm³ is selected, the water invasion rate reaches 35 m³/h

at 100 min; while when the density is 1.10 g/cm³, under the same bottom hole pressure difference, the water invasion rate is only 15 m³/h within the same time. The core mechanism of this phenomenon is: the initial supporting effect of low-density drilling fluid on bottom hole pressure is weak, resulting in a small initial driving force for water invasion (the difference between formation pressure and bottom hole pressure). Although the subsequent mixing of water will further reduce the density of the mixed fluid, the low initial driving force makes the overall growth rate of water invasion gentle; while the initial bottom hole pressure of high-density drilling fluid is high, and the initial driving force for water invasion is small. However, with the occurrence of water invasion, the density of the mixed fluid decreases rapidly, the bottom hole pressure drops sharply, and the driving force increases rapidly, ultimately leading to a rapid rise in water invasion rate.

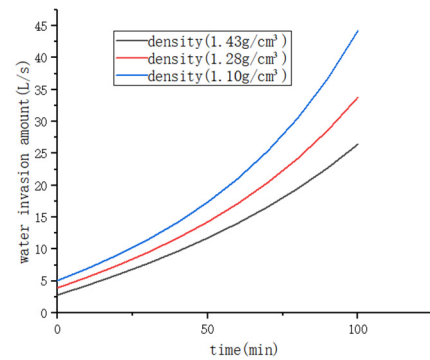


Figure 4. Variation of water invasion rate with circulation time under different drilling fluid densities

2) Influence of Reservoir Open Thickness on Water Invasion Rate

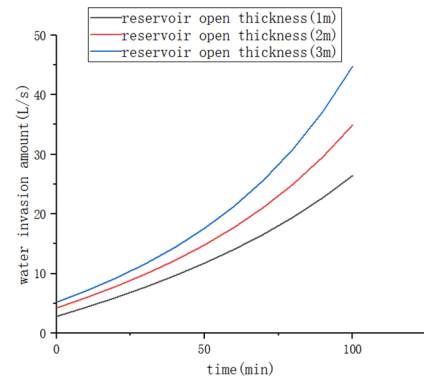


Figure 5. Variation of water invasion rate with circulation time under different open thicknesses

Figure 5 reflects the correlation law between reservoir open thickness and water invasion rate: the larger the reservoir open thickness, the greater the water invasion flow rate and the faster the growth rate. When the open thickness increases from 1 m to 3 m, the water invasion rate increases from 10 m³/h to 45 m³/h at 100 min. The essential reason is that the reservoir open thickness determines the contact area between the wellbore and the formation. The larger the thickness, the more seepage channels and the larger the total cross-sectional area, and the "channel capacity" for formation water invasion is improved; at the same time, the larger contact area makes the mixing efficiency between water and drilling fluid higher during water invasion, the annular pressure drops more obviously, and water invasion is further promoted, forming a

positive feedback cycle of "increased contact area - increased water invasion amount - pressure drop - accelerated water invasion".

3) Influence of Reservoir Open Thickness on Water Invasion Rate

As shown in Figure 6, there is a significant linear positive correlation between reservoir permeability and water invasion flow rate: when the permeability increases from 20 mD to 40 mD, the water invasion rate at each moment increases approximately proportionally, and the water invasion rate increases from 15 m³/h to 30 m³/h at 100 min. This law is consistent with Darcy's seepage law. Permeability is the core parameter characterizing the seepage capacity of the formation. The higher the permeability, the smaller the flow resistance of formation water in the porous medium, and the more water invades the wellbore per unit time under the same pressure difference.

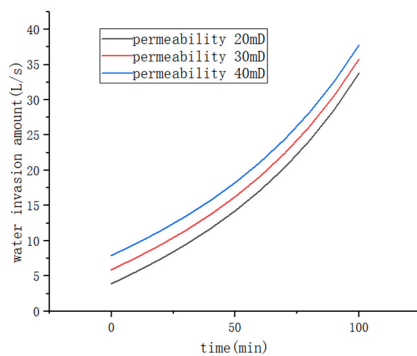


Figure 6. Variation of water invasion rate with circulation time under different permeabilities

4) Influence of Reservoir Open Thickness on Water Invasion Rate

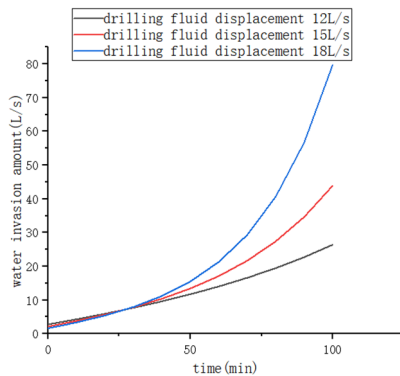


Figure 7. Variation of water invasion rate with circulation time under different drilling fluid displacements

It can be seen from Figure 7 that when the drilling fluid displacement increases, the water invasion rate grows faster, showing an obvious positive correlation trend: when the displacement increases from 12 L/s to 18 L/s, the water invasion rate increases from 30 m³/h to 75 m³/h at 100 min. This phenomenon is the result of the combined action of two opposite effects: on the one hand, the increase in displacement leads to an increase in annular pressure loss, the bottom hole pressure rises, forming an inhibitory effect on water invasion; on the other hand, the high displacement accelerates the migration speed of the invading water in the annulus, making the water move away from the bottom hole faster, reducing the "buffering" effect on the bottom hole pressure. At the same time, the upward migration of the mixed fluid leads to a

decrease in the fluid density near the bottom hole, and the water invasion driving force increases. Among them, the latter has a greater impact on the water invasion rate, dominating the water invasion increment, and ultimately showing that the water invasion rate grows faster at high displacement.

5. Conclusion

Aiming at the overflow problem caused by advanced water injection development in the "three-low" reservoirs of Changqing advanced water injection areas, this study clarifies the overflow influence mechanism and key prevention and control points through laboratory experiments, rheological model optimization, and numerical modeling. The core conclusions are as follows:

Overflow is the result of the coupling effect of multiple factors including geology, drilling, and fluid: reservoir permeability, open thickness, and the superposition of multiple pressure systems constitute the geological basis, and the water invasion risk of high-permeability and large-thickness reservoirs is significantly increased; the rheological properties of drilling fluid are mainly affected by temperature and pressure, which are the core regulatory factors for overflow prevention and control; there is a critical threshold of 20% performance deterioration for injected water invasion, and the stability of drilling fluid directly determines the overflow development trend.

The Herschel-Bulkley rheological model is the optimal fitting model with an average relative error of only 2.43%. The temperature-pressure coupled rheological parameter prediction model (yield stress, flow behavior index, consistency coefficient) established based on this model has a prediction error $\leq 3.12\%$, which can meet the requirements of accurate wellbore pressure calculation under high-temperature and high-pressure conditions.

There is a strong coupled transient effect between water invasion and annular pressure. The established annular pressure calculation model can accurately quantify the influences of parameters such as drilling fluid density, formation parameters, and displacement on water invasion rate; the smaller the drilling fluid density, the slower the growth of water invasion flow rate; the larger the reservoir open thickness and the higher the permeability, the greater the water invasion flow rate (permeability has a linear relationship with water invasion flow rate); when the drilling fluid displacement increases, migration acceleration dominates the water invasion increment, and the water invasion rate grows faster at high displacement.

The results of this study provide theoretical support for the refined prevention and control of overflow in Changqing advanced water injection areas, and offer references for drilling safety guarantee in similar water injection areas.

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