Novel Evaluation Method for Flushing Efficiency Based on the Principle of Wall Shear Rate Equality under High Temperature and High Pressure

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ABSTRACT: An excellent flushing efficiency evaluation device is indispensable for studying the cementing flushing fluid. However, the existing flushing efficiency evaluation device cannot simulate the formation and flushing process of the downhole mud cake. Therefore, this paper proposes a novel flushing efficiency evaluation device that can simulate the formation and flushing of downhole mud cakes. The rotational speed of the device during flushing and the rotor’s diameter is deduced based on the principle of equal wall shear rate. The evaluation device and method can be used to quantitatively evaluate the flushing efficiency of the flushing liquid on the mud cake under high temperatures and high pressures. This device analyzed the effects of the annular gap, temperature, construction displacement, and flushing fluids on flushing efficiency. The results show that the smaller the annular gap, the higher the temperature, the larger the displacement, the higher the scouring efficiency, and the higher the shear bond strength. Fiber flushing has the dual function of mechanical and chemical flushing, so its flushing efficiency is 14.75% higher than that of heavy flushing fluid at 10 min. The surfactant in the emulsified rinse leads to a sudden increase in rinse efficiency in the middle and late stages. The reduced flushing efficiency of the flushing fluid is due to the reduced $\zeta$ potential.

1. INTRODUCTION

In recent years, complex deep wells have become the main exploration frontier in the world.\(^1\) With the drilling operation advancing to deeper oil and gas wells, developing high-temperature and high-pressure (HTHP) drilling fluid has become a trend.\(^2,3\) Under differential pressure, the fluid in the drilling fluid will penetrate the surrounding formation of the well wall. At this time, the solid particles and polymers in the drilling fluid will be filtered out and form mud cake on the well wall (Figure 1a).\(^4\) The mud cake is beneficial for drilling because it will reduce fluid loss and ensure wellbore stability.\(^5\) However, the interface between the formation and cement sheath is critical to the integrity and environmental protection of oil and gas wells.\(^6\) HTHP drilling fluid makes it difficult to remove from the formed mud cake, which will always exist between the cement sheath and well wall. As time increases, polymer degradation in mud cake will lead to cracking of mud cake.\(^7\) In addition, the cement hydration absorbs the water from the mud cake and causes its water contraction, which also causes the interface to produce microcracks.\(^11\) Thus, the cement sheath and formation rock are stripped to form microcracks, reducing the bonding strength of the two interfaces, resulting in the cement sheath seal being ineffective, leading to oil, gas, and water channeling, and reducing the service life of oil and gas wells (Figure 1b).\(^15,17\) Research shows that as long as there is mud cake, regardless of how thin it is, it will form a nondurable interlayer r on the well wall, affecting the shear bonding strength and cementing quality.\(^18\) Therefore, mud cake must be removed before the cement is cemented with the formation rock.

Mud cake is generally removed by mechanical or chemical methods.\(^3\) Due to the uncertainty of geology, lithology, and formation fluid, the effect of mechanical methods is not apparent. Therefore, flushing fluid to remove mud cake on well wall is considered the most effective method (Figure 1c).\(^19\) However, different drilling fluids used in different oil and gas wells and the high-temperature environment make it difficult to determine the system of flushing fluid. In the past decades, various flushing fluids have been developed, and various chemicals have been used.\(^3\) For example, new cemented flushing fluid (wd-c)\(^14\) and nano flushing fluid\(^21\) were used for removing mud cake of water-based drilling fluid; new oil in water nano emulsion flushing fluid was used for removing oil-based drilling fluid mud cake;\(^22,23\) vegetable oil-based microemulsion;\(^24\)
encapsulated thermochemical fluid was added to the flushing fluid to dissolve the mud cake; and diethylenetriamine pentaacetic acid is combined with other catalysts to remove mud cake formed by barite based drilling fluid. The effectiveness of the flushing fluid in removing mud cake needs to be evaluated before field application. Therefore, an effective device and method are needed to evaluate the flushing efficiency of the flushing fluid under formation conditions to ensure effective mud cake removal and improve cementing quality (Figure 1d).

With the development of cementing industry for a long time, many evaluation devices and methods for flushing efficiency have emerged. For example, Leding et al. only formed mud cakes at room temperature and pressure by rotating viscometers, and the mud cakes were only attached to the surface of the core. Chen et al. soaked the core in drilling fluid to form mud cake at high temperatures without pressure difference and then soaked it in flushing fluid to simulate flushing. Wang et al. formed mud cakes on the rotor of the rotary viscometer and then filled the beaker with flushing fluid to evaluate the flushing efficiency by weighing it. Wanderley Neto et al. and da Silva et al. evaluated flushing efficiency at room temperature by applying drilling fluid evenly to the cup wall and then using a rotary viscometer. Ba geri et al. formed mud cake through static filtration of drilling fluid at HTHP and then measured the flushing efficiency at HTHP. However, mud cake formed under the static pressure is easy to be flushed away, resulting in a significant error. Berry and Beall formed mud cake on the circular filter paper at the bottom of the container by stirring the instrument under high temperatures and pressures and then measured the flushing efficiency under the same experimental conditions. Some of these evaluation devices and methods do not consider the high-temperature and high-pressure environment in the well, some do not consider the formation process of mud cake underground, and some set the speed at will in the flushing process.

In the downhole environment, mud cake formation depends on the well’s HTHP environment. However, in the downhole environment, HTHP environment, the mud cake formed by dynamic filtration of drilling fluid and the rotational speed of the flushing fluid in the well will affect the final mud cake flushing efficiency. When flushing the mud cake, the rheological characteristics of the fluid determine the wall shear rate on the well wall, which affects the flowing velocity of the flushing slurry in the annulus, and then affects the flushing efficiency of the mud cake. Therefore, a flushing efficiency evaluation device and method should be developed under HTHP, which can simulate the formation process of mud cake well bottom environment and satisfy the principle of the same wall shear rate under different flushing fluids.

This paper proposes a new device and method for evaluating flushing fluid’s flushing efficiency under HTHP conditions. The calculation model of rotational rate during flushing was deduced based on the principle of equal wall shear rate. By the model, the relationship between the rotor speed of Newton fluid, Bingham fluid, and power-law fluid on annular gap and displacement is finally obtained. The experimental device and method can optimize the flushing fluids of a well. The device and method can
simulate the formation of mud cake in the wellbore under HTHP; based on the principle of equal wall shear rate, the flushing efficiency under different annular gaps and displacement is simulated. To verify the feasibility of the device and method, the differences in mud cake formation under normal temperature and normal pressure (NTNP) and HTHP were compared. Three kinds of flushing fluids and drilling fluids were selected to analyze the effects of the annular gap, construction displacement, and temperature on the flushing efficiency and shear bonding strength, and the primary optimization of the flushing fluids was carried out. Finally, an example of flushing fluid for a well is analyzed using the device and method.

2. ROTATIONAL RATE CALCULATION MODEL

2.1. Wall Shear Rate of Rotor. Suppose concentric cylinders of infinite length are filled with a viscous incompressible fluid (Figure 2). The inner cylinder has a radius of \( R_1 \) and rotates at a constant angular velocity of \( \omega_1 \). The outer cylinder has a radius of \( R_2 \) and rotates at a constant angular velocity of \( \omega_2 \). According to Li et al., \(^{32} \) we obtained the velocity distribution law of fluid rotating in the annular region between coaxial cylinders:

\[
V_\theta = \frac{1}{R_2^2 - R_1^2} \left[ r (\omega_2 R_2^2 - \omega_1 R_1^2) - \frac{R_2^2 R_1^2}{r} (\omega_2 - \omega_1) \right].
\]

(1)

The device used in our experiment is that the inner cylinder does not move, and the outer cylinder rotates, that is, \( \omega_1 = 0 \), and the outer cylinder rotates at the angular velocity of \( \omega_2 \). Eq 2 is obtained.

\[
V_\theta = \frac{\omega_2}{R_2^2 - R_1^2} \left[ r R_2^2 - \frac{R_2^2 R_1^2}{r} \right].
\]

(2)

The corresponding wall shear rate is

\[
g = \frac{2 \omega_2 R_2^2 R_1^2}{r^2 (R_2^2 - R_1^2)}
\]

(3)

When a section of cylinder with height \( h \) is intercepted, the moment acting on it can be calculated as

\[
\tau = \frac{M}{2\pi^2 h}
\]

(4)

When the outer cylinder rotates, i.e., \( r = R_y \), the relationship between the angular velocity of the outer cylinder and the rotational speed \( \omega = 2\pi n/60 \) is substituted into eq 3 to obtain the wall shear rate of the inner cylinder

\[
g_2 = \frac{mn}{15 \left( 1 - \frac{R_1^2}{R_2^2} \right)}
\]

(5)

where \( g_2 \) is the wall shear rate, \( s^{-1} \); \( n \) is the rotating speed of outer cylinder, \( \tau/\min \); \( R_1 \) is the radius of the inner cylinder, \( m \); and \( R_2 \) is the radius of the outer cylinder, \( m \).

It can be seen from eq 5 that when the size of the inner and outer cylinders of the evaluation device is certain when the measured liquid is a Newtonian fluid, the shear rate of the inner cylinder wall is only related to the rotation speed of the outer cylinder, but has nothing to do with the property of the measured liquid.

When the viscous flushing fluid or double effect isolation fluid to be measured is non-Newtonian fluid, the variation law of shear rate on the outer wall of the inner cylinder is completely different from that of Newtonian fluid. The shear rate of the former will vary with the rheological properties of the liquid to be measured, while the latter is independent of the rheological properties of the liquid because it is a Newtonian fluid. To make the application scope of the evaluation device wider, it is necessary to theoretically deduce the relationship between the shear rate of non-Newtonian fluid and Newtonian fluid to correct the measurement of non-Newtonian fluid and obtain more accurate results.

It is assumed that the inner radius of the outer cylinder of the device is \( R_1 \), and the rotational angular velocity is \( \omega \). The outer radius of the inner cylinder is \( R_y \), the height is \( h \), and the liquid rotation torque \( M \) of each layer under laminar flow is constant. Now take any layer of liquid with the radius of annular gap \( x \), and its angular velocity is \( \omega_x \). The side area of liquid layer \( S_x = 2\pi x h \) can get the shear rate at radius \( x \):

\[
g_x = \frac{dv_x}{dx} = \frac{x \, d\omega_x}{dx}
\]

(6)

From eq 4

\[
\frac{dx}{x} = -\frac{2\tau_x}{\gamma}
\]

Substitute eq 7 into eq 6 to obtain

\[
d\omega_x = -\frac{\gamma_x}{2\tau_x} \, dx
\]

(8)

Combined with known conditions, when \( x = R_1 \): \( \omega_x = 0, \tau_x = \tau_{11} \); when \( x = R_y \): \( \omega_x = \omega, \tau_x = \tau_2 \). Integrate eq 8 to obtain

\[
\omega_x = \int_{\tau_1}^{\tau_2} \frac{-\gamma_x}{2\tau_x} \, d\tau_x
\]

(9)

This way, the relationship between shear rate, shear stress, and rotational angular velocity is established. Next, it is solved by substituting with the rheological model. To consider various rheological models, the Robertson Steve model (from now referred to as the Ross model) is selected here \( \tau = A(C + \gamma)^n \).

Because this model includes the Newton, Bingham, and power-law models, it has universal significance.

The shear rate formula of the Ross rheological model is
\[ \gamma = \left( \frac{r}{A} \right)^{1/B} - C \]  

Substituting eq 10 into eq 9

\[ \omega = \int_0^{R_2} \left[ C - \left( \frac{r}{A} \right)^{1/B} \right] \frac{dr}{2\pi} \]  

Among them, \( \tau_1 = \frac{M}{2\pi R_2 R}, \tau_2 = \frac{M}{2\pi R_1 R} \), substitute the two into eq 11 and calculate the integral to obtain

\[ \omega = \frac{1}{2} B \left( \frac{\tau_1}{A} \right) \frac{1}{R_2^{1/B}} - \frac{1}{R_2^{1/B}} - C \ln \frac{R_2}{R_4} \]  

After transformation and comparison with eq 10, we can get

\[ \left( \frac{\tau_1}{A} \right) = \left( 2\omega + 2C \ln \frac{R_2}{R_4} \right) \frac{R_2^{1/B}}{B(R_2^{1/B} - R_1^{1/B})} = \gamma_1 + C \]  

Take \( \omega = 2m/60 \) and substituting into eq 13, the shear rate at the wall of the inner cylinder can be obtained \( \gamma_1 \)

\[ \gamma_1 = \frac{0.20944m}{B \left( 1 - \left( \frac{R_1}{R_4} \right)^{1/B} \right)} + \frac{2C \ln \frac{R_2}{R_4}}{B \left( 1 - \left( \frac{R_1}{R_4} \right)^{1/B} \right)} - C \]  

Analyze and discuss eq 14

\[ \gamma_N = \frac{m}{15B \left( 1 - \left( \frac{R_1}{R_4} \right)^{1/B} \right)} \]  

When \( B = 1 \) and \( C \neq 0 \), it is Bingham mode, and the shear rate of the outer wall of the inner cylinder is

\[ \gamma_N = \frac{m}{15B \left( 1 - \left( \frac{R_1}{R_4} \right)^{1/B} \right)} + (b - 1)C \]  

where \( \gamma_N \) is the wall shear rate of Bingham fluid, \( s^{-1}; C = \frac{5}{\eta} \)

\[ b = \frac{2\pi^2}{R_1^2 - R_1^2} \ln \frac{R_2}{R_1} \]

When \( B \neq 1 \) and \( C = 0 \), it is a power-law mode, and the shear rate of the outer wall of the inner cylinder is

\[ \gamma_M = \frac{m}{15B \left( 1 - \left( \frac{R_1}{R_4} \right)^{1/B} \right)} \]  

2.2. Wall Shear Rate of Wellbore. When the annular gap is small, the annular flow can be regarded as the flow between two plates; that is, the equations derived from the flow between plates can be used to describe the annular flow approximately.

Let the fluid flow in the annulus with the radius \( R_1 \) of the inner tube and the radius \( R_2 \) of the outer tube (Figure 3). For the coaxial annular cylinder with the length \( L \) and the distance \( r \) from the center of the annular gap, we can obtain the wall shear rate

\[ \gamma = \frac{DA \times r}{\mu \times L} \]

At the inner wall of the outer pipe and the outer wall of the inner pipe \( (R = (R_2 - R_1)/2) \), the fluid velocity is 0, that is, \( u = 0 \). The velocity when \( r \) is in the center of the annulus is \( u \). This boundary condition is substituted into eq 18 to integrate the separation variables, and the velocity distribution formula in the annular flow velocity ladder region can be obtained

\[ u = \frac{\Delta p}{2\mu L} \left( \frac{R_2 - R_1}{2} \right)^3 - r^2 \]  

When \( r = r_0 \), the velocity of flow core can be obtained from eq 19

\[ u = \frac{\Delta p}{2\mu L} \left( \frac{R_2 - R_1}{2} \right)^3 - r_0^2 \]  

The flow \( Q \) of the entire annular gap is the sum of the flow \( Q_i \) in the inner speed ladder area, the flow \( Q_o \), in the core, and \( Q_s \) in the outer speed ladder area. That is

\[ Q = Q_i + Q_o + Q_s \]

Among them

\[ Q_i = \int_{r_0}^{R_2 - R_1/2} u \cdot 2\pi r \left( \frac{R_2 + R_1}{2} \right)^2 - r^2 \]  

\[ Q_o = 2\pi r_0 \left( \frac{R_2 + R_1}{2} \right)^2 r_0 \]  

\[ Q_s = \int_{r_0}^{R_2 - R_1/2} u \cdot 2\pi r \left( \frac{R_2 + R_1}{2} \right)^2 + r^2 \]  

Substituting eq 19 into eq 22 and eq 24, substituting eq 20 into eq 23 for calculation, and substituting the results into eq 22, we obtain

\[ Q = \pi(R_2^2 - R_1^2) \frac{\Delta p(R_2 - R_1)}{12\mu L} \]  

According to the definition of hydraulics, the average velocity is

\[ V = \frac{Q}{\pi(R_2^2 - R_1^2)} = \frac{\Delta p(R_2 - R_1)^2}{12\mu L} \]  

If the inner diameter of the outer pipe is \( D_2, D_2 = 2R_2 \). If the outer diameter of the inner pipe is \( D_1, D_1 = 2R_1 \). Substituting
them into eq 25, the annulus pressure drop formula can be obtained after sorting

\[ \Delta P = \frac{48\mu LV}{(D - D_1)^2} \]  
(27)

Substituting eq 27 into eq 18, where \( r = (R_2 - R_1)/2 = (D_2 - D_1)/4 \), the shear rate formula of the annulus wall can be obtained

\[ \gamma = \frac{12V}{D_2 - D_1} \]  
(28)

Substituting eq 26 into eq 28, the relationship between annular displacement and wall shear rate can be obtained

\[ \gamma = \frac{48Q}{\pi(D_2^2 - D_1^2)(D_2 - D_1)} \]  
(29)

2.3. Rotational Rate of Rotor. The flushing fluid flow in the annulus between the casing and the wellbore is similar to the flow between two coaxial cylinders (Figure 4). Based on the principle of equal shear rates, the field cementing parameters (annular gap and construction displacement) were evaluated using the flushing efficiency of laboratory experiments. Combining eq 15 with eq 29, the formula of flushing slurry speed of the Newtonian fluid is obtained

\[ n = \frac{12Q\left(1 - \frac{R_1}{R_2}\right)}{\pi^2(D_2^2 - D_1^2)(D_2 - D_1)} \]  
(30)

where \( R_1 \) is the radius of core, m; \( R_2 \) is the radius of the rotating outer cylinder, m; \( D_1 \) is the diameter of casing, m; \( D_2 \) is the outer diameter of the wellbore, m; Q is the construction displacement, m³/min; and \( n \) is the speed of flushing slurry, r/min.
Combining eq 16 with eq 29, the formula of flushing slurry speed of Bingham fluid is obtained

\[
n = \frac{12Q \left(1 - \frac{R_2^2}{R_1^2}\right)}{n \pi \left(D_2^2 - D_1^2\right)
\]

\[
- \frac{250t_\theta \left(1 - \frac{R_2^2}{R_1^2}\right) \left(2R \ln \frac{R_2}{R_1} - R_2 - R_1\right)}{m \eta}
\]

where \(R_1\) is the radius of core, \(m\); \(R_2\) is the radius of the rotating outer cylinder, \(m\); \(D_1\) is the diameter of casing, \(m\); \(D_2\) is the outer diameter of the wellbore, \(m\); \(Q\) is the construction displacement, \(m^3/min\); \(n\) is the speed of flushing slurry, \(r/min\); \(t_\theta\) is the dynamic shear force of Bingham fluid, \(Pa\); and \(\eta\) is the plastic viscosity, \(mPa\cdot s\).

Combining eq 17 with eq 29, the formula of flushing slurry speed of power-law fluid is obtained

\[
n = \frac{12QB \left(1 - \frac{R_2^2}{R_1^2}\right)}{n \pi \left(D_2^2 - D_1^2\right)
\]

(32)

where \(R_1\) is the radius of core, \(m\); \(R_2\) is the radius of the rotating outer cylinder, \(m\); \(D_1\) is the diameter of casing, \(m\); \(D_2\) is the outer diameter of the wellbore, \(m\); \(Q\) is the construction displacement, \(m^3/min\); \(n\) is the speed of flushing slurry, \(r/min\); \(B\) is the fluidity index of power-law fluid.

3. EVALUATION OF DEVICE AND METHOD

3.1. Device. 3.1.1. Mud Cake Formation, Flushing, and Cement Sheath Curing. Figure 5 shows the overall structure of the device developed in this study. It mainly includes the following three functions: (A) mud cake formation: to simulate the dynamic filtration formation of mud cake on the core wall under HTHP; (B) flushing: to simulate the flushing under HTHP, different construction displacement and annular gaps, and the flushing efficiency under different flushing speeds and different flushing times can be evaluated to optimize the flushing fluids; (C) cement sheath curing: to simulate cement sheath curing under HTHP.

The main body of the device is composed of a pressure curing kettle, electromagnetic-driven mixing system, temperature control system, booster pump, pneumatic hydraulic pipeline system, data acquisition and processing system, flushing fluid, or drilling fluid storage tank. The core components required to implement functions (A, B, and C) are shown in Figure 6. The rotor rotation can simulate the dynamic formation of mud cake at high temperature and pressure, and the flushing flow rate can be determined based on the annulus clearance and construction displacement. The metal rod at the top of the core is to prevent the flow field at the top of the core from being disturbed during mixing. After the rotor is removed, the cement slurry was poured into the annular space to simulate the curing of the cement sheath at HTHP.

3.1.2. Rotor Diameter. When the shear rates across the wall are equal, we can get a formula

\[
\frac{12V}{D_2 - D_1} = \frac{\pi n}{15 \left(1 - \frac{R_2^2}{R_1^2}\right)}
\]

(33)

3.2. Methods. 3.2.1. Mud Cake Formation. This experiment mainly simulates the formation process of mud cake by filtration of drilling fluid. To truly restore the environment in the well, the appropriate stirring barrel radius should be selected according to the annular gap on site before the experiment. Put the core into the core gripper and the whole into the pressure curing kettle. The drilling fluid in the storage tank is pumped into the curing kettle, nitrogen is pumped into it, and the temperature control and pressure program are edited to simulate formation temperature and pressure. Start the electromagnetic drive agitator to simulate the circulation of drilling fluid in the well, and the rotor speed is \(N\). After the heating and pressure boost, the water loss valve of the device is opened, and the filtration time is \(T\) hours. Then, the drilling fluid is pumped back to the drilling fluid storage tank, and the core gripper is taken out to observe the mud cake shape.

3.2.2. Mud Cake Flushing. The formula calculates the reasonable rotor speed, and the flushing fluid is pumped into the device to simulate the flushing process under the formation temperature and pressure. The flushing time is determined according to the requirements of the turbulent contact time of the flushing fluid in the cementing site. After the flushing, the flushing fluid pump is returned to the flushing fluid storage tank, and the core gripper is taken out to observe the flushing condition of the mud cake.

3.2.3. Flushing Efficiency Calculation. The flushing efficiency of the flushing fluid (\(\eta\)) can be calculated according to eq 35 using the mass of the mold and core before flushing (\(M_0\)), the mass of the mold and core after mud cake formation.
and the mass of the mold and core after flushing with the flushing fluid \( (M_2) \).

\[
\eta = \frac{M_1 - M_2}{M_1 - M_0} \times 100\% \tag{35}
\]

3.2.4. Cement Injection and Maintenance. After flushing, the core gripper was taken out, the cement stone mold was installed (simulated casing, inner diameter 80 mm, height 50 mm), and the annulus of the core and cement stone mold was filled with cement slurry, as shown in Figure 8. After filling the cement slurry, the glass rod is used to stir the cement slurry at a uniform speed in the same direction for 30 s to eliminate bubbles in the slurry to avoid bubbles affecting the cement strength during subsequent curing. After adding the end cover, it was put into the curing kettle and a certain age was maintained in the setting temperature and pressure water bath curing (Figure 9).

3.2.5 Shear Bonding Strength Test. After curing, the core was taken out as a whole (Figure 8), and its shear bonding strength was measured on a digital flexural and compressive testing machine. The compressive strength is measured by the conventional “pressing out method”. Then, eq 36 \(^{55} \) was used to calculate the shear bonding strength. The schematic diagram of the shear bonding strength test is shown in Figure 7.

\[
P = \frac{F}{10 \times \pi \times D \times H} \tag{36}
\]

3.2.6. Experimental Scheme. The specific evaluation process of flushing efficiency of flushing fluid and shear bonding strength of cement stone is shown below.
4. COMPARISON OF EVALUATION DEVICES

4.1. Experimental Materials. The core is 24.5 mm in diameter and 75 mm in length, with a gas permeability of \((9-11) \times 10^{-3} \, \mu m^2\). Three flushing fluids and three drilling fluids were used in this experiment. The flushing fluids are: (a) Fiber flushing fluid: diluted flushing fluid + 0.2% fiber (the main raw material of cleaning fiber is inert white silk polypropylene, density 1.0 g/cm\(^3\)). (b) Emulsion flushing fluid: 3% emulsifier + 0.5% sodium silicate + 1.4% compound surfactant + 5% potassium chloride. (c) Heavy flushing fluid: water + 53.3% weighting agent A + 3% BXR-200L (density 1.19 g/cm\(^3\)). The properties of drilling fluids are shown in Table 1, and the composition of the cement slurry system used is shown in Table 2.

4.2. Different Evaluation Device. The mud cake formation and flushing efficiency of the NTNP flushing efficiency evaluation device and the HTHP flushing efficiency evaluation device were compared. Wang developed the NTNP evaluation device,\(^28\) and the HTHP evaluation device was developed by ourselves. The polymer drilling fluid (Table 1) and fiber flushing fluid were used. The experimental temperature is 100 °C, and the pressure is 20 MPa. The speed of the rotor is 300 r/min, the filtration is done for 24 h, and flushing was performed for 10 min. Figure 10 shows the mud cakes formed by the NTNP evaluation device and the HTHP evaluation device. It can be seen from Figure 10 that the mud cake formed by the NTNP evaluation device has a loose structure and low strength, which is a virtual mud cake, while the mud cake formed by the HTHP evaluation device has a dense structure and high strength. To better observe the differences between the mud cakes formed by the two devices and methods, SEM analysis was conducted on some areas of the two mud cakes (Figure 10). The results showed that the mud cake formed under the NTNP was porous and the surface was extremely uneven, while the mud cake formed under the HTHP had fewer and smaller pores, compact structure, and smooth surface. As can be seen in Figure 11, even if water is used as a flushing fluid, the flushing efficiency of mud cake formed by the NTNP device reaches over 90% in 3 min and nearly 100% in about 7 min. However, after the flushing efficiency of the mud cake formed by the HTHP device reaches about 30% at 3 min, the subsequent improvement is very small. The virtual mud cake formed by the NTNP device is easier to flush away. In addition, the flushing efficiency of 30% may be due to some virtual mud cakes on the wall surface, which can be easily flushed away. The rest is solid mud cake. If it is not flushed away, cement hydration will absorb the water in the solid mud cake in the later cementing process, leading to the cracking of the mud cake and the formation oil, gas, and water channeling.

**Figure 10.** Morphology and SEM images of mud cake formed by different devices before and after washing.

**Figure 11.** Relationship between flushing efficiency and time at different devices.
efficiency of the two devices, it can be seen that the process of mud cake formation in the HPHT device is closer to the mud cake formation in the well.

5. ANALYSIS OF INFLUENCING FACTORS OF FLUSHING EFFICIENCY

5.1. Annular Gap. Three different wellbores and casing diameters were selected, and the corresponding rotor radius, core radius, and rotor speed were calculated and are shown in Table 3. The oil-based drilling fluid with emulsion flushing fluid was selected for the experiment; the experiment was carried out at 100 °C × 20 MPa. The mud cakes were formed at a rotating speed of 300 r/min and filtration for 24 h. Construction displacement for flushing is 0.8 m³/min. All flushing efficiency analyses were averaged over three experimental tests. Flushing efficiency and shear bond strength are shown in Figures 2−4, respectively.

From the morphological characteristics of the mud cake on the core surface after flushing (Figure 12), it can be seen that the smaller the annular gap, the less mud cake remains after flushing. The smaller the annular gap, the higher the flushing efficiency (Figure 13). According to eq 28, the smaller the annulus clearance, the higher the shear rate of fluid on the wall. In addition, the shear effect of the flushing fluid in the narrow annulus on the mud cake is stronger, so the narrower the annulus, the higher the flushing efficiency. The shear rates corresponding to the three annular gaps are 98, 310, and 356 s⁻¹, respectively. The shear rate of the narrow annular gap is more than 3 times that of the wide annular gap. Therefore, the flushing efficiency of the narrow gap annulus is higher. Figure 13 also shows that flushing efficiency increased with flushing time. After flushing for 5 min, there is a significant increase in the flushing efficiency, which may be reflected in the dilution of mud cake by the surfactant in the emulsified flushing fluid. However, after 7 min, the growth trend slows down, indicating that under this system, the flushing time of 7 min has reached an excellent flushing effect, and the flushing efficiency reaches more than 90%. The flushing efficiency of wells with a small annular gap is much higher than that of Wells with a large annular gap. The shear bonding strength increases gradually as the flushing time increases (Figure 14). The shear bonding strength can also indirectly reflect the flushing efficiency. The higher the shear bond strength, the cleaner the mud cake flushing. Therefore, the variation trend of shear bond strength is consistent with the variation trend of flushing efficiency.

5.2. Temperature. The oil-based drilling fluid with emulsified flushing fluid, wellbore diameter of 152.4 mm, and...
casing diameter of 101.6 mm was used to investigate the effect of temperature on flushing efficiency. The mud cakes were formed at a rotating speed of 300 r/min and filtration for 24 h. Construction displacement for flushing is 0.8 m³/min, and the pressure for the experiment is 20 MPa. From the morphological characteristics of the mud cake on the core surface after flushing (Figure 15), the mud cakes on the wall surface have been cleaned after flushing for 10 min at different temperatures. The effect of temperature on flushing efficiency cannot be directly seen from the appearance. The higher the temperature, the higher the flushing efficiency and the smaller the difference in flushing efficiency (Figure 16). Due to surfactants in the emulsion flushing solution, which adsorb on the surface of the material to reduce the interface surface tension, the surface wettability of the material changes, which can improve the flushing efficiency. With the increase in temperature, the interfacial tension of surfactant decreases, the van der Waals force between surfactant and mud cake decreases, and the thickness of the boundary layer around surfactant decreases, so the flushing efficiency is very high. This is also why the flushing efficiency at low temperatures differs little or even equally, indicating that the increase in temperature will increase the flushing efficiency and shear bonding strength to the limit value at a certain time, and there will be no change.

5.3. Construction Displacement. Three flushing fluids construction displacements are 0.8, 1.0, and 1.2 m³/min. Take fiber flushing fluid as an example to flush polysulfonic drilling fluid. The well diameter is 215.9 mm, the casing diameter is 139.7 mm, the drilling fluid rotation speed is 300 r/min, and the filtration time is 24 h. Experiments were carried out at 100 °C × 20 MPa. From the morphological characteristics of the mud cake on the core surface after flushing (Figure 18), it can be seen that the larger the construction displacement, the less mud cake remains after flushing. And the more significant the construction displacement, the higher the flushing efficiency (Figure 19). According to eq 29, the larger the displacement, the higher the shear rate of the fluid on the wall. In addition, the larger displacement has a stronger shear effect on the mud cake, so the larger the displacement, the higher the flushing efficiency. This is similar to the effect of annular clearance. The shear rates corresponding to the three construction displacements are 98, 122, and 147 s⁻¹, respectively. The shear rate of the three construction displacements is a little different. Therefore, the flushing efficiency difference is more uniform. The shear bonding strength increases gradually as the flushing time increases (Figure 20). The shear bonding strength can also indirectly reflect the flushing efficiency. The higher the shear bonding strength, the cleaner the mud cake flushing. At high temperatures, the shear bonding strength differs little or even equally, indicating that the increase in temperature will increase the flushing efficiency and shear bonding strength to the limit value at a certain time, and there will be no change.

Figure 15. Morphological characteristics of mud cake before and after flushing at different temperatures.

Figure 16. Relationship between flushing efficiency and flushing time at different temperatures.

Figure 17. Relationship between shear bonding strength and flushing time at different temperatures.

Figure 18. Relationship between flushing efficiency and flushing time at different temperatures.
Through the above experiments, the influences of annulus gap, temperature, and construction displacement on flushing efficiency and shear bonding strength were analyzed, and the following conclusions were obtained (Table 4).

5.4. Flushing Fluids. Three different flushing fluids were used for flushing the mud cake formed by polymer drilling fluid. The flushing fluid displacement was 1.0 m³/min, and the rotor speed was 370 r/min. The well diameter was 215.9 mm, the casing diameter was 139.7 mm, the drilling fluid rotational speed was 300 r/min, and the filtration time was 24 h. Experiments were carried out at 100 °C × 20 MPa. From the morphological characteristics of the mud cake on the core surface after flushing (Figure 21), it can be seen that emulsified flushing fluid and fiber flushing fluid have a good flushing effect on polymer drilling fluid mud cake. The wall surface of the heavy flushing fluid after flushing still has a layer of obvious mud cake. Figure 22 also shows that the flushing efficiency of polymer drilling fluid mud cake is not significantly improved by adding heavy flushing fluid. The heavy flushing fluid contains a large amount of organic salt potassium formate. The more organic salt, the more ζ potential drop, resulting in a higher repulsion, leading to a poor flushing effect on mud cake, while the flushing effect of fiber flushing fluid on mud cake is obvious in the early stage of flushing. This may be due to the fibers removing the mud cake from the formation by two mechanisms: mechanical cleaning and attracting non-aqueous compounds from mud cakes, so in the early stage of flushing, flushing efficiency rises quickly. And the emulsified fluid’s flushing efficiency is increased more obviously as the flushing time increases, which is consistent with the rule observed above. The surfactant in the emulsified flushing fluid in the middle and late periods plays a role. The shear bonding strength increases gradually as the flushing time increases (Figure 23). The shear bonding strength can also reflect the flushing efficiency of the three flushing fluids. The higher the shear bond strength, the cleaner the mud cake flushing. Therefore, the variation trend of shear bond strength is consistent with the variation trend of flushing efficiency. Therefore, for the well with an annular gap of 38.1 mm and the use of polymer drilling fluid to achieve a good flushing effect, two flushing fluid construction schemes can make the flushing efficiency close to 90% and significantly improve the flushing efficiency. (1) With emulsified flushing fluid, the flushing time was 8 min when the displacement was 1 m³/min. The rinse liquid dosage is 8.32 m³. (2) With fiber flushing fluid, the flushing time is 6 min when the displacement is 1 m³/min. The fiber flushing liquid dosage is 6.25 m³.

6. APPLYING
Xinsha 101 is a horizontal well. The well was drilled to 3407 m with a 215.9 mm drill bit with polysulfonic drilling fluid (Table
The bottom hole temperature was 85 °C, and the temperature set in the experiment was 80 °C. According to 4.3–4.6, emulsified flushing fluid and fiber flushing fluid have a better flushing effect on the mud cake of drilling fluid. Therefore, the flushing fluid in this scheme adopts emulsified flushing fluid + fiber, and the specific formula is as follows: 3% emulsifier + 0.5% sodium silicate + 1.4% compound surfactant + 5% potassium chloride + 0.3% fiber. To eliminate the interference of mud cake thickness heterogeneity on subsequent flushing efficiency evaluation, the experimental conditions for simulating mud cake dynamic formation were the same (80 °C × 20 MPa × rotational speed 300 r/min × filtration time 24 h), and the core permeability was also the same. Field drilling fluid was selected, and an indoor evaluation experiment was conducted according to the construction design steps of the flushing fluid. The flushing time was 8 min. The wall shear rate under different construction displacements is shown in Table S, and the flushing efficiency and shear bonding strength are shown in Figure 24.

Table 5. Rotor Speed Corresponding to Construction Displacement

| construction of displacement (m³/min) | 0.64 | 0.76 | 1.0 | 1.2 | 1.5 |
|--------------------------------------|------|------|-----|-----|-----|
| wall shear rate (s⁻¹)                | 78   | 94   | 122 | 148 | 185 |

The larger the construction displacement, the higher the flushing efficiency (Figure 24). However, when the construction displacement increases to 1.0 m³/min, the flushing efficiency and shear bonding strength are not significant in the construction displacement alone. Therefore, when the construction displacement is 1.0, 1.2, and 1.5 m³/min, respectively, the change of flushing efficiency and shear bonding strength with flushing time is further verified by experiments.

The larger the displacement, the higher the flushing efficiency and the shear cementation strength (Figures 25 and 26). Three conditions were taken: the construction displacement was 1.0 m³/min, flushing time was 7 min, and flushing efficiency was more than 90%; the construction displacement was 1.2 m³/min, flushing time was 6 min, and flushing efficiency was more than 90%; and the construction displacement was 1.5 m³/min, flushing time was 5 min, and flushing efficiency was above 90%. Therefore, the alternative is: (1) The construction displacement was 1.0 m³/min, flushing time was 7 min, and flushing fluid dosage was 7.24 m³; (2) the construction displacement was 1.2 m³/min, flushing time was 6 min, and flushing fluid dosage was 7.66 m³; and (3) the construction displacement was 1.5 m³/min, flushing time was 5 min, and flushing fluid dosage was 7.78 m³. The flushing efficiency of these three flushing fluids is more than 90%, and the interface bonding strength is above 2.8 MPa, which can meet the construction requirements.

7. CONCLUSIONS

In this study, an evaluation device for determining the flushing efficiency of flushing fluid was developed. This evaluation device was developed based on the equal wall shear rate principle. The calculation model of the device’s rotor diameter and rotational speed is presented in this paper. We also developed a calculation model of rotor diameter and a flushing efficiency evaluation method. This evaluation device and method can be used to
quantitatively evaluate the flushing efficiency of the flushing fluid under the HTHP and help workers select the flushing fluids. We used the device and method to evaluate the influence of different evaluation devices, annular gaps, temperature, and construction displacement on flushing efficiency and shear bonding strength. The following are the results obtained:

(1) Due to the different environments of mud cake formation, the flushing efficiency of mud cake formation under NTNP is 61.34% higher than that under HTHP.

(2) The wall shear stress generated by the fluid flow during the flushing process is negatively correlated with the annulus gap and positively correlated with the construction displacement. The higher the wall shear rate, the higher the flushing efficiency, so the more significant the displacement, the smaller the annular gap, the higher the flushing efficiency, and the higher the shear bond strength.

(3) The temperature affects the flushing efficiency of the flushing fluid. When the temperature increased from 80 to 120 °C, the average flushing efficiency increased by 2.86% and the shear bonding strength increased by 0.472 MPa.

(4) The average efficiency of fiber flushing fluid solution was 2% higher than that of emulsion flushing fluid solution before 7 min, but it was lower than 1.5% after 7 min.

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B.Y. contributed to Writing—original draft preparation. S.Y. contributed to writing—reviewing and editing. B.X. involved in methodology. S.Z. performed data curation and language check. P.L. analyzed data statistics (PDF).

Notes
The authors declare no competing financial interest.

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NOMENCLATURE

- $V_\phi$: tangential velocity component
- $R_i$: radius of the inner cylinder, m
- $\omega_c$: velocity of the outer cylinder, rad/s
- $\gamma_m$: wall shear rate, s$^{-1}$
- $\Delta P$: annulus pressure drops
- $\tau$: shear stress, N/m$^2$
- $\gamma_n$: wall shear rate of a Newtonian fluid, s$^{-1}$
- $B$: fluidity index
- $\eta$: plastic viscosity, mPa·s
- $w_c$: velocity, m/s
- $D_1$: outer diameter of the inner pipe, m
- $P$: shear bonding strength, MPa
- $D_2$: diameter of core, m
- $R_o$: radius of the outer cylinder, m
- $\omega_n$: velocity of the inner cylinder, rad/s
- $r$: assumed boundary condition, m
- $n$: rotating speed of outer cylinder, r/min
- $M$: friction torque generated by the liquid layer at r, N·m
- $A$: consistency coefficient
- $\gamma_m$: wall shear rate of power-law fluid, s$^{-1}$
- $C$: shear rate correction
- $\mu$: absolute viscosity, mPa·s
- $Q$: construction displacement, m$^3$/s
- $D_2$: outer diameter of appearance, m
- $F_c$: measured force, kN
- $H$: contact length of core, mm

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