Research Article

Cuttings Transport Models and Experimental Visualization of Underbalanced Horizontal Drilling

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Aerated underbalanced horizontal drilling technology has become the focus of the drilling industry at home and abroad, and one of the engineering core issues is the horizontal borehole cleaning. Therefore, calculating the minimum injection volume of gas and liquid accurately is essential for the construction in aerated underbalanced horizontal drilling. This paper establishes a physical model of carrying cuttings and borehole cleaning in wellbore of horizontal well and a critical transport mathematical model according to gas-liquid-solid flow mechanism and large plane dunes particle transport theory.

1. Introduction

With the development of horizontal drilling oriented technology and thin formation of oil and gas reservoirs, aerated underbalanced horizontal drilling technology has become the focus of the drilling industry at home and abroad, and one of the engineering core issues is the horizontal borehole cleaning when gas-bearing mud exists [1–3]. Therefore, calculating the minimum injection volume of gas and liquid accurately is essential for the construction in aerated underbalanced horizontal drilling. To calculate the required minimum injection volume of gas and liquid accurately which can safely carry cuttings, it is necessary to carry out the researches of carrying cuttings theory and visualization experiment of particle motion in depth.

2. Transport Law Analysis of Cuttings in the Horizontal Wellbore

2.1. Particularity of Cuttings Transport in Horizontal Well.
The cuttings' distributions in horizontal section and vertical section are shown in Figures 1 and 2. When the rock is broken by bit, the large particle cuttings can transport smoothly at drill collar because of the high flow rate, but when they reach the drill collar and drill pipe junction large particle cuttings are accumulated due to the annulus area sudden increase. Contrasting vertical section and horizontal section [4, 5], we can find that in vertical section the larger cuttings will fall to the bottom of the well then be repeatedly broken, but in horizontal section once the large cuttings are produced which the fluid cannot carry, these cuttings will only stay at the lower side of the wall waiting for drill tool rolling until forming small particles to be carried by fluid to downstream.

2.2. Horizontal Well Cuttings Movement Form.
In horizontal well cuttings transportation can be divided into suspension, rolling, and saltation.

2.2.1. Suspension.
Suspension is an important way of cuttings movement. The form of the suspension is drift with drilling fluid. In suspension there are two kinds of force, one is gravity which makes cuttings settle down to the lower side of the wall and another kind is gas-liquid two-phase flow driving force which makes cuttings particle move to downstream along the wellbore. The speed of cuttings moving to downstream is related to the speed of gas-liquid two-phase flow,
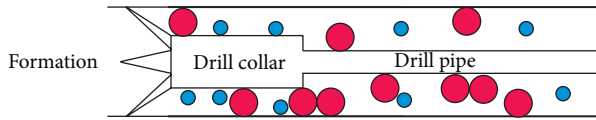
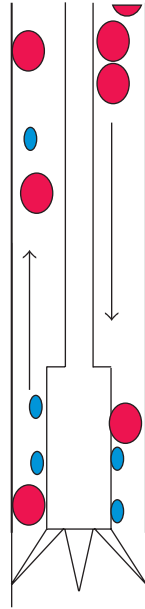FIGURE 1: Cuttings distribution in horizontal section.

FIGURE 3: Cuttings suspension diagram in multiphase flow condition.

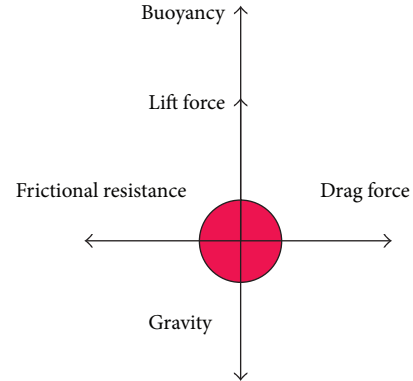FIGURE 2: Cuttings distribution in vertical section.

FIGURE 4: Cuttings rolling force in horizontal well.

FIGURE 5: Cuttings rolling schematic diagram in horizontal well.

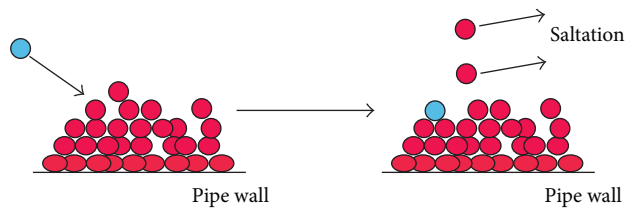FIGURE 6: Cuttings saltation schematic diagram in horizontal section.

the transportation volume of cuttings can indirectly represent the speed of cuttings moving to downstream, and the greater the flow, the more it carried cuttings. In settling process suspended particles are brought back to the top by eddy current that makes the cuttings drift up and down. As a result, the settling velocity becomes slow. Suspension of cuttings schematic diagram is shown in Figure 3.

2.2.2. Rolling. When flow drag force is greater than particle resistance, the particles located in the surface outstanding position of cuttings bed begin to move in the form of slipping. Because of the rough wall surface, slipping often converts into rolling and the cuttings always keep contact with the lower side of the wall, the force as shown in Figure 4 and cuttings rolling schematic diagram as shown in Figure 5.

2.2.3. Saltation. When the jumping cuttings fall to the lower side of the wall, it will impact the cuttings bed, and the force is related to the jump height and drilling fluid velocity [6–8]. If the cuttings jump low, the momentum obtained from the fluid is small and they will stop jumping. If not, they will jump again. The jumping height is inversely proportional to the drilling fluid density. This special movement is called saltation, cuttings saltation force as shown in Figure 6.

3. Carrying Cuttings Model of Multiphase Flow in Horizontal Well Annulus

3.1. Cuttings Rolling. When cuttings are based on single particle rolling on the lower side of the wall, with the effect of the gas-liquid two-phase flow, they transport to the downstream [9].

3.1.1. Cuttings Particle Rolling Force Analysis. When the gas-liquid flow rate is small, the particles first roll in single in the wall, and the forces include: drag force F_D produced by air current, friction force F_{friction} along the contact surface between the particle and the wall, gravity G, buoyancy
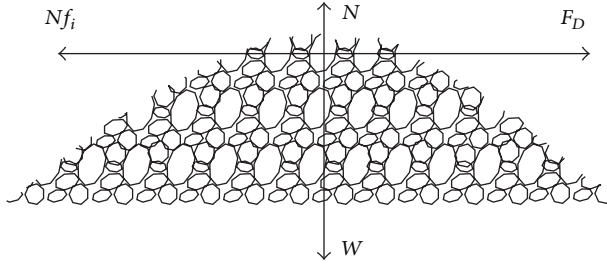
FIGURE 7: The force analysis of cuttings accumulation.

FIGURE 8: Horizontal experiment facilities.

F_{buoyancy}, and support N on longitudinal, as shown in Figure 4.

3.1.2. Cuttings Particle Rolling Starting Condition. It is necessary to build a horizontal mathematical equation to determine the minimum gas liquid volume when single particle cuttings roll forward [10]:

$$C_D \frac{\rho_m v_m^2}{2} \frac{\pi d_s^2}{4} = kG,$$
$$v_m = \frac{q_l + q_g}{A},$$

(1)

where C_D is resistance coefficient, dimensionless; ρ_m is fluid density, kg/m³; v_m is fluid velocity, m/s; d_s is cuttings particle diameter, m; k is friction resistance coefficient, dimensionless; G is cuttings particle gravity, N; q_l is liquid phase flow rate, m³/s; q_g is gas phase flow rate, m³/s; A is flow area, m².

The minimum velocity v_m can be derived from the different particle gravity G and different materials friction resistance coefficient k.

3.2. Cuttings Saltation

3.2.1. Cuttings Particle Rolling Force Analysis. When cuttings transport in the annulus, the forces mainly include gravity, resistance, the saffman lift force, buoyancy, basset force, pressure gradient force, added mass force and magnus effect force in underbalanced drilling [11, 12]; force analysis is as shown in Figure 7. In the horizontal section, cuttings gravity is the main force to constitute horizontal friction resistance, and the calculation formula is

$$W = \rho_s V_s g,$$

(2)

where W is cuttings particle gravity, N; ρ_s is cuttings particle density, kg/m³; V_s is cuttings particle volume, m³; g is gravity acceleration coefficient, m/s².

The driving force of the cuttings is mainly gas-liquid two-phase dragging force. The dragging force is influenced by many factors like the Reynolds number, cuttings size, cuttings shape, flow state, and fluid compressibility [13, 14]. Its direction is consistent with the speed of fluid relative to the particles, and the calculation formula is

$$F_D = C_D \frac{\rho_m (v_m - v_s)^2}{2} \frac{\pi d_s^2}{4},$$

(3)

where F_D is dragging force, N; C_D is dragging coefficient, dimensionless; v_m is fluid velocity, m/s; v_s is cuttings particle transport velocity, m/s; d_s is cuttings particle diameter, m.

3.2.2. Cuttings Particle Rolling Starting Condition. Cuttings particle group located in cuttings bed and flow boundary presents a state of bulk material accumulation [15]. The bulk materials limit equilibrium equation of cuttings particles can be signified as follows:

$$T_{\text{lim}} = N f_i + FA,$$

(4)

where T_{lim} is the ultimate shear force making the particle moves, N; N is internal force effecting on the particle, N; f_i is internal friction coefficient of bulk material accumulation, dimensionless; F is unit cohesion, N/m²; A is flow area, m².

According to the force analysis of cuttings particles as shown in Figure 8, ignoring cohesive force and buoyancy [16], the accumulation particles limit force balance equation can be deformed into

$$F_D = f_i W,$$

(5)

where $T_{\text{lim}} = F_D$, $N = W$.

f_i can be determined by experiment. In general, f_i is of particle group ε, given as

$$f_i = \mu_i + \frac{\alpha/\beta}{e^{\alpha(\varepsilon - 0.26)} - 1 + \alpha/\beta},$$

(6)

where ε is void fraction of particle group, dimensionless; α, β is parameters related to cuttings accumulation degree, dimensionless; μ_i is internal friction coefficient of particles, dimensionless.

When saltation starts, force balance formula can be derived by combining formula (2), (3), and (6) as follows:

$$C_D \frac{\rho_m v_m^2 \pi d_s^2}{8} = \left[\mu_i + \frac{\alpha/\beta}{e^{\alpha(\varepsilon - 0.26)} - 1 + \alpha/\beta} \right] \frac{\pi d_s^3}{6} \rho_s g,$$

(7)

where v_m is fluid flow velocity under granular limit balance state; when v_m continues to increase, the balance will be broken and cuttings will begin to transport, m/s.

4. The Visualization Experiment of Horizontal Section

This study establishes an annulus visualization organic glass experimental facility (total length 25 m, experimental annulus outer tube and inner diameter 140 mm, inner tube outer diameter 63 mm, inner tube inner diameter 55 mm), which uses compressed air and water as experiment flow and simulation cuttings (equivalent diameter 6 mm) as experiment medium, developing critical carrying cuttings in different liquid injections and tests the hydrodynamic parameters. Then we can get borehole cleaning critical carrying cuttings data in different experiment conditions.

4.1. Experiment Research Content

(1) Simulation of multiphase flow and carrying cuttings large bench in horizontal section (simulation of the rotating drill pipe in rotary drilling)

(2) Simulation of multiphase flow and carrying cuttings large bench in horizontal section (simulation of the slide drilling and circulation after stopping drilling).

4.2. Experimental Facilities.
Experimental facilities which simulate air flow condition at certain range of pressure and flow rate down the hole include experimental bench, air compressor, gas tank, water tank, liquid pump, and flow meter, as shown in Figure 8. Experiment testing part is monitoring and recording pipe section pressure, gas flow rate, liquid flow rate, image of the phenomenon, and so forth.

4.3. Experiment Process.
The simulation cuttings are injected in different speeds at the bottom, maintaining a certain amount of gas injection and then increasing the liquid injection (liquid injection can be controlled from 0~5 L/s) until the cuttings are suspended in the experiment pipe section; at this time the gas flow rate is considered as the critical flow rate. The liquid flow rate was ratcheted up after injecting the liquid for 2 minutes steadily, and the experiment was stopped until the cuttings of the bottom are carried out completely. The test parameters include liquid injection, gas injection, liquid flow velocity, cuttings velocity, and cuttings concentration. Flow pressure is controlled from 0.1 MPa to 0.6 MPa throughout the experiment.

4.4. Experiment Phenomena

(1) When the drill string is rotating, experiment phenomena are shown in Figures 9 and 10.

(2) When the drill is immovability, experiment phenomena are shown in Figures 11, 12, and 13.

Through the observation, comparing with the drill which is immovability, when the drill string is rotating it has a viscous impact on the surrounding drilling fluid due to its viscosity, and then cuttings on the cuttings bed are agitated, so the effect of carrying cuttings is better in conditions of

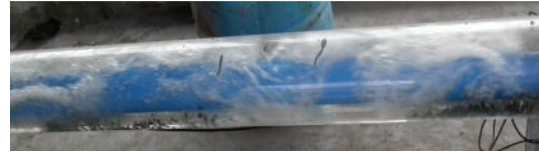Figure 9: The formation of the cuttings bed.

Figure 10: Cuttings transport.

Figure 11: The drill is 100% eccentric.

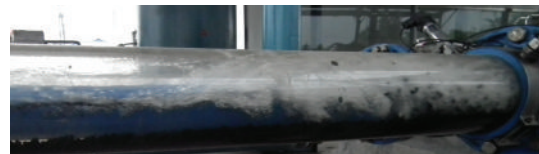Figure 12: The formation of the cuttings bed.

Figure 13: Cuttings transport.

injecting the same volume of gas. The way of cuttings transport is mainly saltation.

4.5. Experimental Data and Processing Results

(1) When the drill string is rotating, calculation results in different injecting volumes of gas and liquid (see Table 1).

(2) When the drill is immovability, calculation results in different injecting volumes of gas and liquid (see Table 2).

Through the previous experimental data and phenomena, comparing with the drill which is immovability, the drill rotating can make the water acts as the simulation drilling fluid moving in spirals and the pressure of annular flow field distributing in fluctuation forms. At the same time, when

TABLE 1: Calculation results in different injecting volumes of gas and liquid (rotating).

Liquid injection (l/s)	Gas injection (m³/h)	Model mixing speed (bottom) (m/s)	Critical mixing speed (bottom) (m/s)	Error between model and real (%)
0.87	65	0.72	1.05	45.9%
1.3	70	0.80	0.96	20.8%
1.86	90	1.04	1.32	26.8%
2.17	95	1.11	1.37	23.2%
2.6	120	1.40	1.64	17.5%
3.25	130	1.52	1.73	13.4%
Average error				24.6%

In Table 1 the critical flow speed refers to the minimum mixing speed when cuttings start to saltate. In the condition attaining to the critical carrying cuttings, comparing the speed calculated by multiphase flow simulation software with the real mixing speed of gas-liquid two-phase flow, the error is concluded and then the current carrying cuttings model is amended.

TABLE 2: Calculation results in different injecting volumes of gas and liquid (immovability).

Liquid injection (l/s)	Gas injection (m³/h)	Model mixing speed (bottom) (m/s)	Critical mixing speed (bottom) (m/s)	Error between model and real (%)
0.87	90	0.99	1.29	30.2%
1.3	115	1.28	1.59	24.5%
1.86	130	1.46	1.73	18.6%
2.17	150	1.67	1.91	14.4%
2.6	170	1.88	2.11	12.5%
3.25	190	2.09	2.28	9.3%
Average error				18.3%

In Table 2 the critical flow speed refers to the minimum mixing speed when cuttings start to saltate. In the condition attaining to the critical carrying cuttings, comparing the speed calculated by multiphase flow simulation software with the real mixing speed of gas-liquid two-phase flow, the error is concluded and then the current carrying cuttings model is modified.

the drill string is rotating it will have a viscous impact on the surrounding drilling fluid due to its viscosity, and then cuttings on the cuttings bed are agitated, so the effect of carrying cuttings is better in conditions that injecting the same volume of gas.

5. Model Modification

5.1. Critical Carrying Cuttings Mathematical Model Modification in Horizontal Well (Rotation).
From the result of experimental data, the real minimum continuous carrying cuttings comprehensive speed is the equal of 124% of saltation critical velocity as a modification model, given as

$$v_m = 1.24 \sqrt{\left[\mu_i + \frac{\alpha/\beta}{e^{\alpha(\varepsilon-0.26)} - 1 + \alpha/\beta}\right] \frac{4d_s}{3C_D\rho_m}\rho_s g}, \quad (8)$$

where $\tau_i = f_i\rho_m(v_m - v_s)^2$, stratified flow is $f_i = 64/N_{Re}$, and turbulent (slug flow, agitation flow, and annular mist flow) is

$$f_i = \left[1.14 - 2\lg\left(\frac{e}{D} + \frac{21.25}{N_{Re}^{0.9}}\right)\right]^{-2}, \quad (9)$$

where μ_i is internal friction coefficient of particles, dimensionless; α, β are parameters related to cuttings accumulation degree, dimensionless; f_i is gas-liquid interface friction coefficient, dimensionless; τ_i is stress between mixture and wall

shear, Pa; ρ_m is mixture real density, kg/m³; v_m is gas-liquid mixing velocity, m/s; C_D is drag coefficient, dimensionless, function of Re; v_s is cuttings particle transport velocity, m/s; d_s is cuttings particle diameter, m; ρ_s is cuttings particle density, kg/m³; N_{Re} is the Reynolds number; D is pipe diameter, m.

5.2. Critical Carrying Cuttings Mathematical Model Modification in Horizontal Well (Immovability).
From the result of experimental data, the real minimum continuous carrying cuttings comprehensive speed is the equal of 124% of saltation critical velocity as a modification model when the drill is rotating, namely,

$$v_m = 1.18 * 1.24 \sqrt{\left[\mu_i + \frac{\alpha/\beta}{e^{\alpha(\varepsilon-0.26)} - 1 + \alpha/\beta}\right] \frac{4d_s}{3C_D\rho_m}\rho_s g}$$

$$= 1.46 \sqrt{\left[\mu_i + \frac{\alpha/\beta}{e^{\alpha(\varepsilon-0.26)} - 1 + \alpha/\beta}\right] \frac{4d_s}{3C_D\rho_m}\rho_s g}, \quad (10)$$

where $\tau_i = f_i\rho_m(v_m - v_s)^2$, stratified flow is $f_i = 64/N_{Re}$, and turbulent (slug flow, agitation flow, and annular mist flow) is

$$f_i = \left[1.14 - 2\lg\left(\frac{e}{D} + \frac{21.25}{N_{Re}^{0.9}}\right)\right]^{-2}. \quad (11)$$

6. Conclusions

(1) Comparing vertical section and horizontal section, in vertical section the larger cuttings will fall to the bottom of the well repeatedly broken, but in horizontal section once the large particle cuttings are produced which the fluid cannot carry, these cuttings will only stay at the lower side of the wall waiting for drill tool rolling until forming small particles to be carried by fluid to downstream.

(2) In horizontal section cuttings transport depending on gas-liquid comprehensive velocity and drilling fluid viscosity is mainly saltation, and the drill rotation benefits cuttings transport. In the condition of carrying cuttings smoothly, when the drill is immovability the comprehensive velocity is 1.18 times as big as when it is rotating. After processing the experimental data, the established mathematic model is modified.

Acknowledgments

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