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Research Article

A Multiparameter Coupled Prediction Model for Annular Cuttings Bed Height in Horizontal Wells

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Cuttings accumulation in horizontal drilling is one of the main reasons for high drilling torque and drag and serious backing pressure and consequently influencing the rate of penetration (ROP), so inhibiting the generation of cuttings bed and keeping the hole clean is an important prerequisite to ensure the smooth and safe drilling of horizontal section. In order to master the formation mechanism of cuttings bed and reveal the influence law of influencing factors, based on the three-layer cuttings bed migration model and the two-phase solid-liquid flow theory, this paper establishes a numerical simulation method for cuttings migration characteristics in the annulus of horizontal wells, reveals the cuttings concentration distribution law and migration characteristics in the horizontal well section, and fits the engineering prediction model of cuttings bed height considering many factors such as geology, engineering, and fluid body according to the simulation results. The analysis of sensitive factors shows that the rate of penetrating, cuttings density, and drill pipe eccentricity is not conducive to borehole cleaning, and cuttings are easy to accumulate to form cuttings bed; increasing the drilling fluid density, displacement, and drill pipe speed is conducive to borehole cleaning and reducing the height of cuttings bed. The research shows that within the range of normal construction parameters, the error of the horizontal cuttings height prediction model is less than 10%, which can meet the needs of engineering analysis. The model provides convenience for engineering applications.

1. Introduction

In petroleum drilling, solid particles (cuttings) are generated by the drill bit which is being pushed downhole with a certain rate of penetration (ROP). The cuttings are subsequently transported by the often shear-thinning drilling fluid through the annular space (created by the drill pipe1 in a wellbore) to the surface [1], as qualitatively depicted in Figure 1.

When drilling complex structural wells such as horizontal wells, extended-reach wells, and multibranch wells, the cuttings in horizontal or slanted sections are easily deposited and form cuttings beds under the influence of gravity [2], which leads to high drilling friction torque, serious supporting pressure, and other engineering complexities. In serious cases, it also leads to accidents such as sand sticking or drilling tool twisting. In addition, the cuttings bed is repeatedly rolled by the drill string (Busch et al., 2020) [3], which is easy to increase the solid content of the drilling fluid increases and reduce the rate of penetrating (ROP) (Nazari T., 2010) [4]. Therefore, it is of great significance to comprehensively consider various factors during drilling and accurately predict the formation of cuttings beds to ensure the safe drilling of complex structure wells.

For a long time, many researchers have conducted numerous experiments (Shadizadeh S. R., 2012) [5] and numerical simulations on the migration of cuttings in the annular borehole. Gavignet and Sobey (1989) [6] proposed a two-layer model to describe cuttings migration in highly deviated wells. The model assumes that the cuttings are deposited at the bottom of the borehole and slide at the bottom of the well, and the upper part is the flow layer of the drilling fluid, and depending on the momentum conservation of the two solid-liquid phases, the migration pattern of cuttings beds is established, focusing on the analysis of the inclination, viscosity of the drilling fluid, drilling pipe

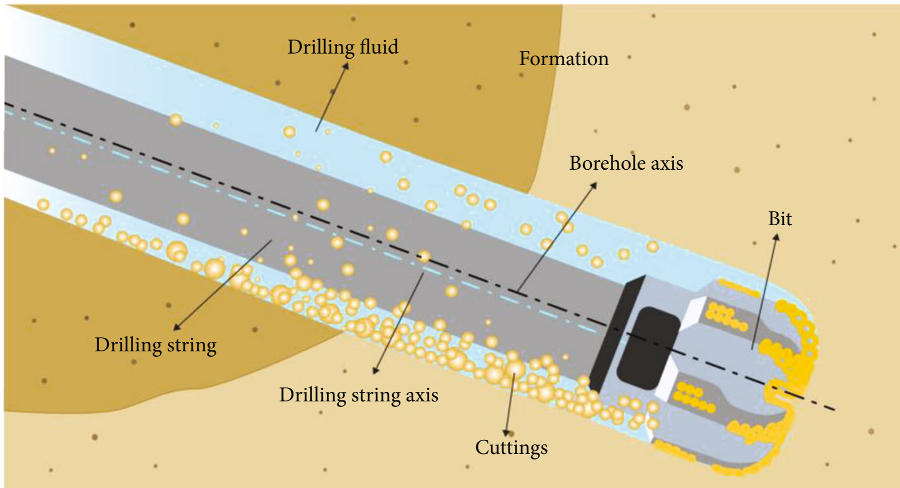

Figure 1: Schematic diagram of cuttings migration in the horizontal annulus.

eccentricity, the size of the drilling tool, borehole size, and mechanical properties. Kamp et al. (1999) [7] found that with the increase of drilling fluid flow rate, some cuttings in the fixed cuttings bed become moving, forming a moving cuttings bed. Doron and Barnea (1993) [8] established three models to describe cuttings migration law according to the mass conservation equation and momentum conservation equation of drilling fluid cuttings two phases in the water well section and inclined well section; however, this model does not consider the factors such as annulus flow, drilling fluid rheology, and cuttings rolling, so it has some limitations. In addition to drilling fluid return velocity and cuttings size, drilling pipe rotation also has a great influence on cuttings migration in the annulus. Ozbayoglu et al. (2008) [9] showed that when the drilling pipe rotation speed increased from 0 to 40 r/min, the ratio of cuttings bed area to total annulus area decreased from 49% to 25%. Analysis shows that the drilling pipe rotation can drive drilling fluid around to rotate together, and the cuttings are carried to the annulus by centrifugal force high-speed area, to obtain more kinetic energy, easy to remove the wellhead. Sorgun et al. (2011) [10] conducted an experimental study on the influence of cuttings migration on pressure loss under the drilling pipe rotation. The results show that cuttings accumulation can cause the pressure drop in the annulus, and the rotation of the drilling pipe can significantly reduce the friction pressure loss of drilling fluid in the wellbore annulus and improve the cleaning efficiency of cuttings in the wellbore annulus. Duan et al. (2010) [11] studied the influence of drill pipe rotation on rock cuttings by experiment and numerical simulation, and results show that the rotation of the drilling pipe has an important influence on cuttings migration, because it can induce spiral flow in the annulus and promote cuttings particle migration. Based on the research status at home and abroad, two-layer model (fixed cuttings bed and suspended layer) (Naganawa et al., 2007) [12] and three-layer model (fixed cuttings bed, mobile cuttings bed, and suspended layer) (Hyun et al., 2000) [13] are mainly used to describe the distribution and migration of cuttings in the annulus. Considering the difficulties of cuttings migration analysis, indoor experiments and numerical simulation are mainly used to carry out the research ROP, rotational speed, the eccentricity of the drilling pipe, inclination angle, drilling fluid performance, displacement, borehole size, and cuttings size and shape are the sensitive parameters affecting cuttings migration in the annulus. Although the above research provides a technical means for the analysis of borehole cleaning and grasps a certain law of core migration, the process of experiment and simulation is complex, which is not convenient for engineering applications.

Considering the complexity of cuttings migration characteristics in the horizontal annulus, to improve the engineering application of cuttings bed height prediction method, a convenient method for cuttings bed prediction is established. The main steps are as followed: first, based on the solid-liquid two-phase flow theory and method of computational fluid dynamics, based on the three-layer cuttings bed migration model, comprehensively considering the suspension, rolling, and sliding migration modes of cuttings and the influence of drill string rotation, the physical and mathematical model of three-layer cuttings dynamic migration in horizontal wells is established; second, the numerical simulation software FLUENT is used to simulate the cuttings migration characteristics in the annulus of horizontal wells, and the cuttings concentration distribution and migration characteristics in the horizontal well section under the condition of multifactor coupling are studied; finally, according to the simulation results, the multiparameter coupling prediction model of cuttings bed height is fitted, and the influence of various influencing factors on cuttings bed height is analyzed. Due to the establishment of an explicit equation considering various influencing factors of cuttings bed height, our research provides convenience for rapid prediction of cuttings bed in engineering and provides favorable support for the implementation of horizontal well hole cleaning measures.

2. Establish the Cuttings Migration Model in the Horizontal Annular

2.1. Physical Model. At present, the three-layer model of cuttings bed is widely used [14], that is, it is assumed that the cuttings in the annulus are divided into three layers when drilling in the horizontal section, and the solid-liquid two-phase in the three layers move in three different forms, including an uneven suspension layer (the uppermost part of the annulus), moving bed (the part of the annulus), and static cuttings bed (the bottom of the annulus). In addition, the mass and momentum can be exchanged between layers, and there is a certain velocity difference between the solid-liquid two phases in the suspension layer; under certain conditions, there may be no cuttings migration in the suspension layer, or the bottom static bed may be whole. The body slides or disappears. The physical model is shown in Figure 2.

In the figure, D is the inner diameter of the horizontal well, m; d is the outer diameter of the drilling pipe, m; h_{sd} is the height of the suspended layer, m; h_{mb} is the height of the moving bed, m; h_{sb} is the height of the static bed, m; e is the eccentricity of the drilling pipe, m. It is considered that the cuttings bed height is the sum of the static bed height h_{sb} and the moving bed height h_{mb}.

Based on the above three-layer migration model, for the convenience of modeling and solving, this paper makes the following assumptions [15–21]:

(1) The drilling fluid is an incompressible power-law fluid

(2) The sliding between the solid and liquid phases only occurs in the suspension layer, where the solid content is small, and the solid migration meets the diffusion law

(3) The cuttings are spherical particles with uniform size

(4) The volume concentration of cuttings in the static bed is 55%, and the chip concentration is 0.8 times that of the uniform layer

(5) Constant temperature flow, that is, the influence of heat transfer is not considered

2.2. Governing Equations. According to the characteristics of cuttings transport in the annulus, the governing equations of solid-liquid two-phase flow are established, including continuity equation and momentum equation [11]. According to the hypothesis of three-layer migration of cuttings in the annulus, there is an obvious velocity slip between cuttings and drilling fluid during cuttings migration. Based on the law of conservation of mass, the continuity equations of solid/liquid phase, moving bed, and static bed can be obtained.

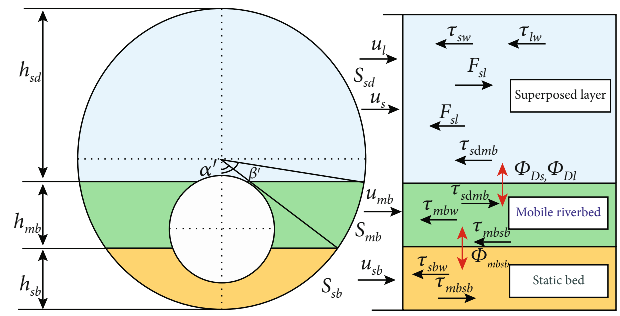

Figure 2: Three-layer model of cuttings migration in the horizontal annulus [14].

$$\begin{cases} \rho_s A_{sd} c_{sd} u_s = m_{ds} - m_{ss}, \\ \rho_l A_{sd}(1 - c_{sd}) u_l = m_{dl} - m_{sl}, \\ \rho_{mb} A_{mb} u_{mb} = m_{ss} + m_{sl} - m_{ds} - m_{dl} + m_{mbsb}, \\ \rho_{sb} A_{sb} u_{sb} = -m_{mbsb}, \end{cases} \tag{1}$$

where c_{sd} is the volume concentration of cuttings in the suspension layer, %; ρ_s and ρ_l are the density of solid phase and liquid phase in the suspension layer, g/cm^3; ρ_{mb} and ρ_{sb} are the average density of moving bed and static bed, g/cm^3; u_s and u_l are the cuttings migration velocity and liquid phase migration velocity in suspension layer, m/s; u_{mb} and u_{sb} are the average migration velocity of moving bed and static bed, m/s; m_{ds} represents the diffusion amount of solid phase and liquid phase in suspension layer, kg/s; m_{ss} and m_{sl} are the sedimentation of the solid and liquid phase in the surface suspended layer, kg/s; m_{mbsb} is the exchange capacity between moving bed and static bed, kg/s.

Based on the hypothesis of three-layer transport of cuttings in the annulus, the force of each layer is analyzed, respectively. Based on the momentum theorem, the momentum equations of the solid/liquid phase in the suspension layer, moving bed, and static bed can be obtained.

$$\begin{cases} \rho_s A_{sd} c_{sd} u_s^2 = -c_{sd} A_{sd} \dfrac{\Delta p}{L} - c_{sd} \tau_{sw} S_{sd} - c_{sd} \tau_{sdmb} c_{sdmb} + F_{sl} + u_{mb} m_{ds} - u_s \phi_{Ss}, \\ \rho_l A_{sd}(1 - c_{sd}) u_l^2 = -(1 - c_{sd}) A_{sd} \dfrac{\Delta p}{L} - (1 - c_{sd}) \tau_{lw} S_{sd} - (1 - c_{sd}) \tau_{sdmb} S_{sdmb} - F_{sl} + u_{mb} m_{dl} - u_l m_{dl}, \\ \rho_{mb} A_{mb} u_{mb}^2 = -A_{mb} \dfrac{\Delta p}{L} - \tau_{mbw} S_{mbw} + \tau_{sdmb} S_{sdmb} - \tau_{mbsb} S_{mbsb} + u_s m_{Ss} + u_l m_{Sl} - u_{mb} m_{ds} - u_{mb} m_{Dl} + u_{sb} m_{mbsb}, \\ \rho_{sb} A_{sb} u_{sb}^2 = -A_{sb} \dfrac{\Delta p}{L} - \tau_{sbw} S_{sbw} + \tau_{mbsb} S_{mbsb} - u_{sb} m_{mbsb}, \end{cases} \tag{2}$$

Table 1: Basic parameters of the simulation.

Parameter	Value	Parameter	Value
Annulus length/m	10	Drilling pipe speed/r·min^{-1}	90
Outer diameter of annulus/mm	248.3	Cuttings density/g·cm^{-3}	2.5
Inner diameter of annulus/mm	127	Cuttings diameter/mm	5
Eccentricity/%	50	Pump delivery/L·s^{-1}	29
Penetration rate/m·h^{-1}	7.5	Drilling fluid density/g·cm^{-3}	1.53

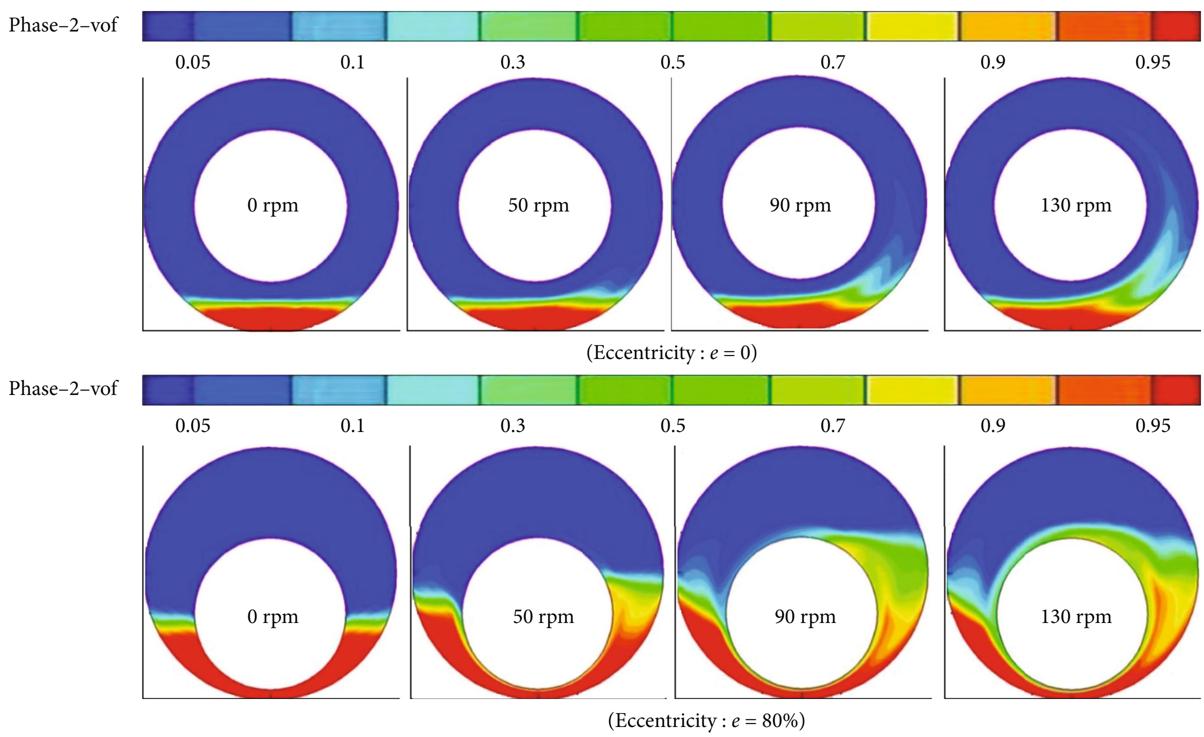

Figure 3: Cloud chart of the cuttings distribution under different rotational speeds.

where $\Delta p/L$ is the pressure gradient, Pa/m; F_{sl} represents the drag force between the liquid and solid in the suspension layer, N/m; τ_{sw}, τ_{lw}, τ_{mb}, τ_{sb}, and τ_{mbsb} represent the shear stress between the solid phase in the suspension layer and the wellbore, the shear stress between the liquid phase in the suspension layer and the wellbore, the shear stress between the moving bed layer and the wellbore, the shear stress between the stationary bed layer and the wellbore, and the shear stress between the fluid in the moving bed layer and the interface of the stationary bed layer, N/m^2.

3. Numerical Simulation of the Migration Characteristics of Cuttings in the Horizontal Annular

According to equations (1) and (2), the governing equation includes four continuity equations and four-momentum equations, including eight unknowns, which are c_{sd}, u_l, u_s, u_{sb}, u_{mb}, h_{sb}, h_{mb}, and $\Delta p/L$, respectively. It can be seen that the model has many influencing factors, and there is a certain coupling relationship. In addition, there are complex contact nonlinearity, geometric nonlinearity, and time nonlinearity, so it is difficult to obtain accurate analytical solutions. In this paper, the computational fluid dynamics software FLUENT is used to simulate the cuttings migration. The Euler multiphase flow model is used as the control model, the structured grid is used for mesh generation, and the second-order upwind scheme is used for numerical iteration [22–27].

3.1. Model Parameters. The horizontal section of the horizontal well is selected for numerical simulation of cuttings migration in the annulus. The length of the model is 10 m, the hole size (outer diameter of the annulus) is 248.3 mm, the hole enlargement rate is 15%, and the outer diameter of the drilling pipe is 127 mm. Other parameters are shown in Table 1.

3.2. Solution Conditions. Initial conditions: mainly including drilling fluid density and rheology, cuttings density and particle size, and drilling pipe speed. See Table 1 for basic settings. The boundary conditions are as follows: (1) the velocity entry boundary condition is adopted at the entrance; (2) the normal exit boundary condition is adopted at the exit; (3) the fixed wall boundary condition is adopted

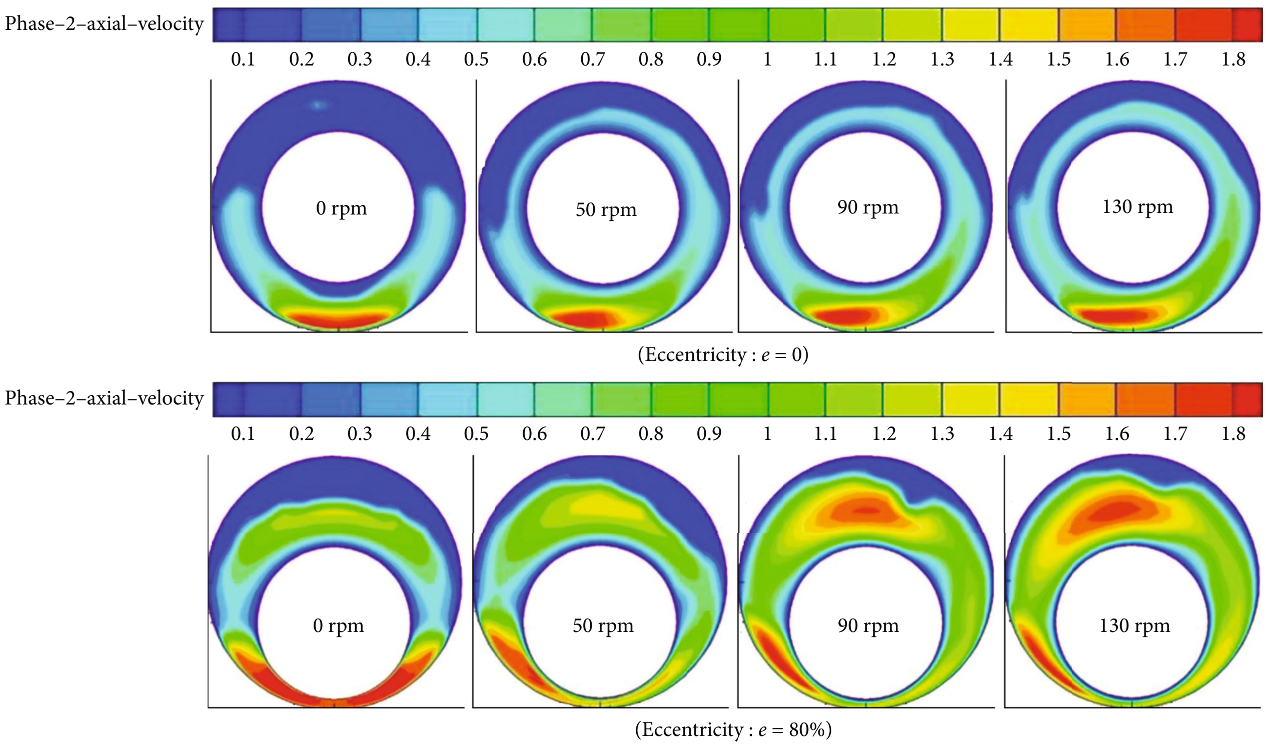

Figure 4: Cloud chart of cuttings migration velocity distribution under different rotational speeds.

at the outer wall of the annulus; (4) the rotating wall boundary condition is adopted at the drill string wall.

3.3. Results Analysis

3.3.1. Distribution Characteristics of the Cuttings Concentration in the Annulus. The cuttings migration in the annulus was simulated when the drilling pipe speed was 0 rpm, 50 rpm, 90 rpm, and 130 rpm, and the cuttings concentration distribution was obtained. The results are shown in Figure 3.

It can be seen from Figure 3 that the drilling pipe rotation has a significant effect on cuttings distribution; with the increase of rotation speed, part of the cuttings in the cuttings bed begins to separate from the bed surface and migrate to the high-velocity area in the annulus, and the greater the rotation speed is, the greater the amount of cuttings is brought into the high-velocity area, which indicates that the drilling pipe rotation is conducive to cuttings migration; in addition, when the rotation speed of the drilling pipe is fixed, the drilling pipe eccentricity can lead to cuttings migration. With the increase of chip bed height, more cuttings are transported due to the rotation of the drilling pipe.

3.3.2. Distribution Characteristics of Cuttings Migration Velocity in the Annulus. In addition, the annular cuttings velocity field is simulated when the drilling pipe speed is 0 rpm, 50 rpm, 90 rpm, and 130 rpm, respectively, and the results are shown in Figure 4.

It can be seen from Figure 4 that the convection caused by the rotation of the drilling pipe causes the cuttings particles to be continuously brought into the upper annulus; when the drilling pipe is stationary or the rotation speed is small, there are almost no cuttings particles in the upper part of the concentric annulus, or only a small amount of cuttings particles migrate; with the increase of the rotation speed of the drilling pipe, the migration speed of the cuttings brought into the upper part of the annulus gradually increases; when the drilling pipe is eccentric, this effect is not obvious. More significantly, with the increase of drilling pipe penetration rate, a large number of cuttings particles are transported radially by the drill string, the high-speed area of cuttings migration gradually moves to the upper annulus, and the area occupied by the high-speed area gradually expands, so that the cuttings migration speed is significantly improved, and the role of promoting cuttings migration is significant.

Consistent with the assumption of the theoretical model, in the simulation results, when the volume concentration of cuttings is greater than 55%, we think that the cuttings are in the static bed, and the concentration of the moving bed is 0.8 times that of the uniform bed. Through a large number of numerical experiments, we can obtain the cuttings bed height under different factors.

4. Establish the Multiparameter Coupling Prediction Model for the Height of the Cutting Bed

Regression analysis of the cuttings migration simulation results can determine the multiparameter coupling prediction model for the height of the cuttings bed, and the results are presented in the following equation:

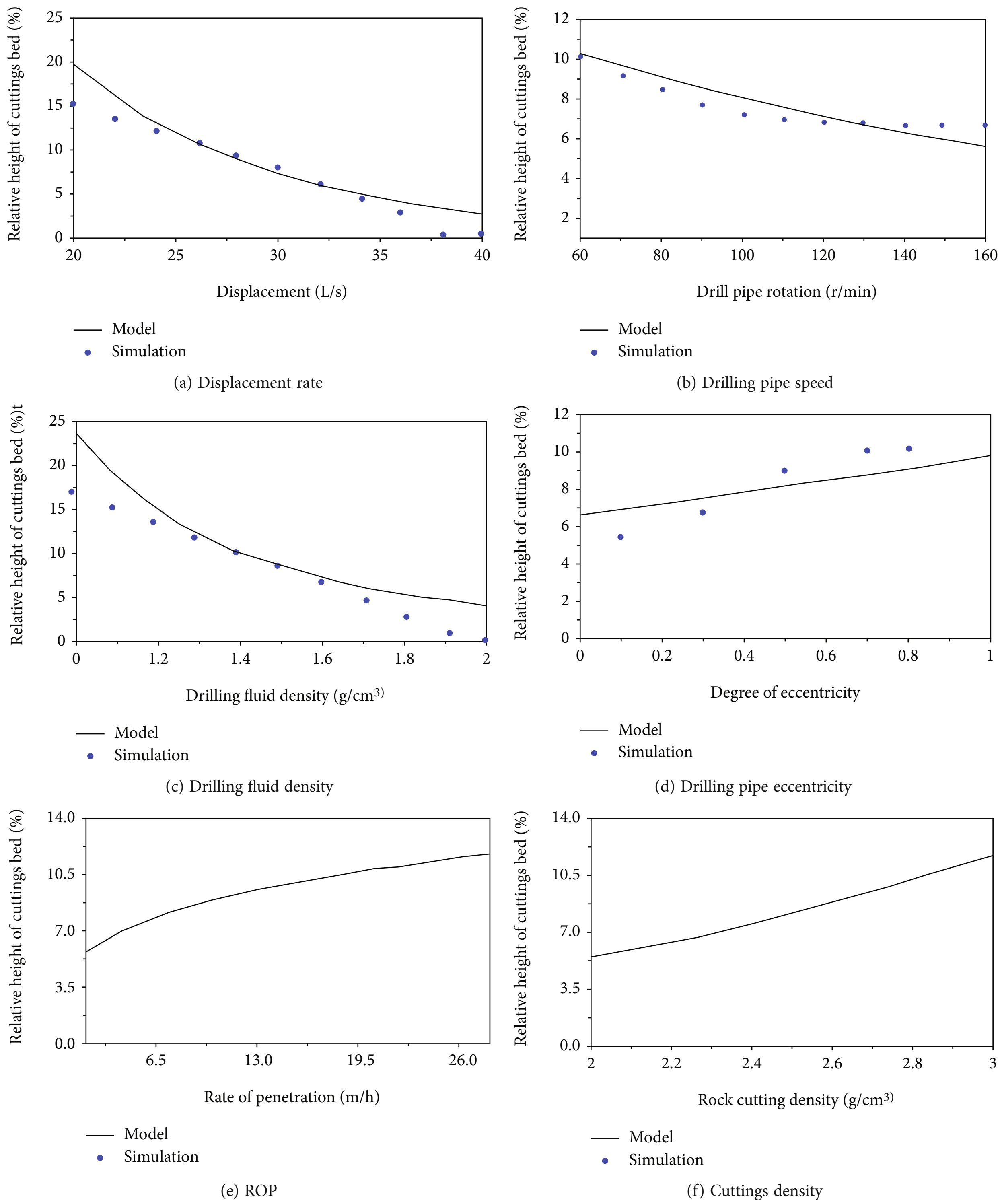

Figure 5: Relative height of cuttings bed under different influence factors.

$$H_c = \frac{d_w}{100}\left\{\frac{2\times 10^{-4}\rho_f^{-2.477}\rho_s^{2}\left(d_w-d_{po}\right)^{0.062}\left(d_w+d_{po}\right)^{-0.276}\left[1450-0.05\left[\mu_e-0.4u_a\left(d_w-d_{po}\right)\right]\right]^{2}d_b^{0.552}}{ROP^{0.276}d_s^{-0.174}(1+0.5e)\left(2.035u_a^{-1.8}-0.762\right)e^{(-0.007RPM)}}\right\}, \quad (3)$$

where H_c is cuttings bed height, m; d_w is borehole diameter (considering enlargement rate), m; d_{po} is drilling pipe outer diameter, m; d_b is drill bit diameter, m; ρ_f is drilling fluid density, kg/cm^3; ρ_s is cuttings density, kg/cm^3; u_a is annular return velocity, m/s; ROP is penetration rate, m/h; d_s is cuttings diameter, m; e is drill rod eccentricity, %; μ_e is effective viscosity, Pa·s.

Depending on the characteristics of the non-Newtonian fluid, it can be determined by the following formula:

$$\text{Power-law fluid}: \mu_e = \frac{K(2n + 1/3n)^{1-n}\left(d_w - d_{po}\right)^{1-n}}{12^{1-n}{u_a}^{1-n}}, \quad (4)$$

$$\text{Bingham fluid}: \mu_e = \mu_\infty + \tau_0 \frac{d_w - d_{po}}{12u_a}, \quad (5)$$

where n is the power-law fluid fluidity index, dimensionless; K is the power-law fluid consistency coefficient, Pa·s^n; μ_∞ is Bingham fluid plastic viscosity, Pa·s; τ_0 is dynamic shear stress, Pa.

It can be seen that the model accounts for the influence of annulus size, cuttings density, cuttings size, drilling fluid density and viscosity, ROP, and the drilling pipe eccentricity. To reveal the influence of sensitive parameters on the relative height of cuttings bed and verify the reliability of the engineering model, the prediction results of the coupled model are calculated and compared with the numerical simulation results, and the comparisons are shown in Figure 5.

It can be seen from Figure 5 that (1) with the increase of displacement, the height of the cuttings bed decreases significantly. When the displacement is 24~34 L/s, the error between the predicted value of the engineering model and the simulated value is small. (2) With the increase of the drilling pipe rotation speed, the height of cuttings bed decreases, and under the conditions of high speed, the error between the predicted value of engineering model and the simulated value is small. (3) With the increase of drilling fluid density, the cuttings bed height decreases significantly. When the drilling fluid density is low or high, there is a certain error between the predicted value of the engineering model and the simulated value. (4) The center of the drilling pipe helps to reduce the cuttings bed height. (5) The cuttings bed height increases with the increase of ROP. (6) The cuttings with high density are easy to form cuttings bed, that is, cuttings density. The higher the degree is, the higher the relative height of the bed is.

5. Summary and Conclusion

(1) Based on the three-layer cuttings bed migration model and the two-phase solid-liquid flow theory of computational fluid dynamics, the migration characteristics of the cuttings in the horizontal annulus are simulated using the numerical simulation software FLUENT. The distribution of the cuttings concentration and migration characteristics in the horizontal section under multifactor coupling conditions are investigated. According to the simulation results, the multiparameter coupling prediction model of the cuttings bed height is fitted. It provides a practical technique for the prediction of the height of the cuttings bed

(2) The multiparameter coupling model of the height of the cuttings bed agrees well with the numerical simulation results, and the error is less than 10% in the normal range of construction parameters, which can meet the requirements of engineering analysis. By analyzing the sensitivity factor of the multiparameter coupling model, it shows that higher ROP, cuttings density, and the drilling pipe eccentricity are not conducive to well cleaning, and cuttings are easy to accumulate and form the cuttings bed; increasing drilling fluid density, displacement, and the drilling pipe speed is conducive to cleaning the wellbore and reducing the height of the cuttings bed

(3) Due to the complexity of establishing the explicit fitting equation, the multiparameter coupling model established in this paper only considers some factors that have a great impact on the height of cuttings bed. In fact, the current neural network and other methods can take more factors affecting the cuttings bed height into account by establishing an implicit function. Therefore, neural network and other methods should be used to predict the cuttings bed height in future research

Nomenclature

D: Inner diameter of the horizontal well, m
d: Outer diameter of the drilling pipe, m
h_{sd}: Height of the suspended layer, m
h_{mb}: Height of the moving bed, m
h_{sb}: Height of the static bed, m
e: Eccentricity of the drilling pipe, m
c_{sd}: Volume concentration of cuttings in the suspension layer, %
ρ_s: Density of solid phase in the suspension layer, g/cm^3
ρ_l: Density of liquid phase in the suspension layer, g/cm^3
ρ_{mb}: Average density of moving bed, g/cm^3
ρ_{sb}: Average density of static bed, g/cm^3
u_s: Cuttings migration velocity in suspension layer, m/s
u_l: Liquid phase migration velocity in suspension layer, m/s
u_{mb}: Average migration velocity of moving bed, m/s
u_{sb}: Average migration velocity of static bed, m/s
m_{ds}: Diffusion amount of solid phase and liquid phase in suspension layer, kg/s
m_{ss}: Sedimentation of the solid in the surface suspended layer, kg/s
m_{sl}: Sedimentation of the liquid phase in the surface suspended layer, kg/s
m_{mbsb}:

Exchange capacity between moving bed and static bed, kg/s
$\Delta p/L$: Pressure gradient, Pa/m
F_{sl}: Drag force between the liquid and solid in the suspension layer, N/m
τ_{sw}: Shear stress between the solid phase in the suspension layer and the wellbore, N/m^2
τ_{lw}: Shear stress between the liquid phase in the suspension layer and the wellbore, N/m^2
τ_{mb}: Shear stress between the moving bed layer and the wellbore, N/m^2
τ_{sb}: Shear stress between the stationary bed layer and the wellbore, N/m^2
τ_{mbsb}: Shear stress at the interface between the moving and stationary bed layer, N/m^2
H_c: Cuttings bed height, m
d_w: Borehole diameter (considering enlargement rate), m
d_{po}: Drilling pipe outer diameter, m
d_b: Drill bit diameter, m
ρ_f: Drilling fluid density, kg/cm^3
ρ_s: Cuttings density, kg/cm^3
u_a: Annular return velocity, m/s
ROP: Penetration rate, m/h
d_s: Cuttings diameter, m
e: Drill rod eccentricity, %
μ_e: Effective viscosity, Pa·s
n: Power-law fluid fluidity index, dimensionless
K: Power-law fluid consistency coefficient, Pa·sn
μ_∞: Bingham fluid plastic viscosity, Pa·s
τ_0: Dynamic shear stress, Pa.

Data Availability

The data used to support the findings of this study are included within the article. The length of the model is 10 m, the hole size (outer diameter of annulus) is 248.3 mm, the hole enlargement rate is 15%, and the outer diameter of the drilling pipe is 127 mm. Other parameters are shown in Table 1.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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