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Research Article

Simulation and Experimental Study on Cuttings-Carrying for Reverse Circulation Horizontal Directional Drilling with Dual Drill Pipes

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In the past decades, horizontal directional drilling (HDD) has been successfully used to install various pipelines in different strata. However, construction accidents such as drill-burying and drill-sticking occur occasionally when pipelines installed by HDD method in an unstable stratum such as sand cobble stratum. Recently, HDD with dual drill pipes was used to install pipelines in unstable stratum, and the effect is significant. The law of cuttings migration for HDD with dual drill pipes is still unclear. Therefore, it is necessary to study the law of cuttings migration in reverse circulation with dual drill pipes. This study performs numerical simulations and experimental research on the cuttings-carrying process in reverse circulation directional drilling with dual drill pipes. Based on the assumption of dual concentric pipes, simulations of fluid-solid two-phase flows are conducted in different flow channels between the inner and outer drill pipes. An experimental cuttings-carrying model is then established. By combining the results of the numerical simulations and experimental investigation, the hydraulic parameters of the dual drill pipe system are optimized, and the rationalities of the drill tool design and the grading selection are validated. The results of this study provide a reference cuttings-carrying model during reverse circulation HDD with dual drill pipes.

1. Introduction

Horizontal directional drilling (HDD) is a technique for installing pipes or utility lines below ground using a surface-monitored drilling rig that launches and places a drill string at a shallow angle to the surface and has tracking and steering capabilities [1]. Compared with traditional open-cut construction, the HDD technology has the advantages of fast construction speed, small damage to the ground, and no effect on the use of existing pipelines [2, 3]. Considering these advantages, the HDD technology has been widely used in various pipelines installations.

For sand cobble stratum, the cementation between the particles is poor, which is a typically unstable stratum [4, 5]. Conventional HDD with single drill pipe often encounters accidents such as drill-burying and drill-sticking when drilling in the unstable stratum [6]. Recently, HDD with dual drill pipes was used to install pipelines in the unstable stratum, and the effect was significant. The law of cuttings migration for HDD with dual drill pipes is still unclear. The law of cuttings migration is a key factor affecting the borehole cleaning. Borehole cleaning is an engineering challenge in horizontal directional drilling, which has received significant attention over the past 30 years, and scholars around the world have conducted substantial amounts of research on this topic. An unclean borehole, which can be caused by the stratum of a large cuttings bed due to extensive accumulation of cuttings in the borehole annulus, can result in high torque, high friction, and high dragging pressure on the drill pipe [7]. In severe cases, the drilling tools may be broken, causing serious engineering accidents, such as sticking [8–10]. Many controllable and uncontrollable factors are involved in the hole-cleaning process (i.e., the cuttings-carrying process), such as the flow velocity in the borehole annulus, the displacement of the mud pump, the viscosity of the drilling fluid, the rotational speed of the drill pipe, and the diameter of the bit waterway [11, 12].

Among the factors affecting the carrying of cuttings in highly deviated wells, the flow velocity in the borehole annulus is the most important, and it is directly determined by the inlet displacement of the ground mud pump. As the flow velocity in the borehole annulus increases, the total concentration of cuttings in the annulus and the ratio of the cuttings bed area to the borehole area decreases [13, 14]. Ozbayoglu et al. [15] studied the carrying of cuttings in the horizontal section of a wellbore at a penetration rate of 9 m/h and found that when the flow velocity in the borehole annulus decreased from 1.2 m/s to 0.6 m/s, the ratio of the cuttings bed area to the wellbore area increased significantly from approximately 0.2% to 0.6%. Engineering and laboratory tests have demonstrated that the rotation of the drilling tool promotes the cutting-carrying during drilling in highly deviated wells. Ozbayoglu et al. [16] showed that when the rotational speed of the drill pipe increased from 0 r/min to 40 r/min, the ratio of the cuttings bed area to the wellbore area decreased from 49% to 28%, and when the speed increased to 120 r/min, the ratio decreased to 20.5%. Therefore, there should be a critical rotational speed of the drill pipe for carrying cuttings, above which an increase in the rotational speed has an insignificant effect on the hole cleaning.

Sun [17] performed numerical simulations of the influences of eight rotational speeds of a drill pipe on carrying cuttings and argued that the rotation of the drill pipe could significantly increase the tangential speed of the drilling fluid, which can prevent the stratum of the cuttings bed to a certain degree. Using computational fluid dynamics (CFD) simulations, this speed was identified to be approximately 160 r/min under high displacement conditions.

Zamora and Hanson [18] investigated the carrying of cuttings in wells with four ranges of deviation angles (0–10°, 10–30°, 30–60°, and 60–90°) and found that the cuttings beds in wells with deviation angles of 30–60° were the most difficult to transport. Based on experimental observations, Okranji et al. [19] suggested that cuttings-carrying is the most difficult in wells with deviation angles of 45–55°. However, Li and Walker [20] found that the deviation angle of the well can influence the thickness of the cuttings bed. At a controlled displacement of 8.33 L/s and a penetration rate of 40 m/h, they found that the thickness of the cuttings bed increased from 6.35 cm to 7.62 cm as the deviation angle increased from 60° to 90°. Therefore, the cuttings bed in the horizontal section is considered to have the largest ratio of the cuttings bed area to the borehole area.

Duan et al. [8] conducted cuttings-carrying experiments at the experimental platform of the Tulsa University Drilling Research Projects (TUDRP) using cuttings with diameters of 0.45–3.3 mm. The experimental fluids were clear water and an aluminum chloride (PAC) polymer solution. When clean water was used as the fluid, fine cuttings were difficult to transport. In contrast, when a 0.25 ppb PAC polymer solution was used as the drilling mud, the fine cuttings were easily transported.

Akhshika et al. [21] conducted cuttings-carrying simulations in highly deviated well sections with cuttings of different shapes. Their results demonstrated the feasibility of using CFD-DEM (discrete element method) to simulate cuttings-carrying and also suggested that unrounded (cube- and disk-shaped) cuttings are more likely to aggregate in highly deviated (40°, 60°, and 80°) well sections.

Over the last decades, Vestavik et al. [22–24] have designed the dual drill pipe system for vertical drilling and studied the effects of downhole tools and mud circulation parameters on the hole cleaning. At the same time, the method of cleaning the borehole is proposed, which has guiding significance for the actual drilling.

Previous studies have exclusively investigated cuttings-carrying in the borehole annulus (the space between the drill pipe and the well wall) of highly deviated well sections under the forward circulation drilling mode. During reverse circulation HDD with dual drill pipes, the drilling efficiency significantly impacted by the cuttings-carrying. However, the cuttings-carrying process in multiple annuli during reverse circulation directional drilling with dual drill pipes is unclear and has not been studied by scholars. Accordingly, this study simulates and experiment the cuttings-carrying process during reverse circulation drilling to provide a reference for the design of the hydraulic parameters for drilling.

2. Methodology

2.1. Introduction of Dual Drill Pipe Reverse Circulation Directional Drilling. Different from the single drill pipe system, the directional drilling system with dual drill pipes consists of an inner drill pipe and an outer drill pipe. The inner drill pipe is connected with the drill bit, and the outer drill pipe is connected with the deviation tool. When drilling, if both inner and outer drill pipes are rotated simultaneously, the drilling hole is a straight line. If only the inner drill pipe is rotated and the outer drill pipe is fixed, the drilling hole will deflect to a certain direction. In addition to controlling deviation, the outer drill pipe can also act as a casing in the drilling process to ensure efficient and safe drilling. Therefore, the directional drilling system with dual drill pipes has a good application in laying pipelines in unstable strata.

As shown in Figure 1, there are three flushing fluid flow channels in dual drill pipe directional drilling system, namely, the annulus between the outer drill pipe and the well wall, the annulus between the inner drill pipe and the outer drill pipe, and the central hole of the inner drill pipe. In all channels, the central hole of the inner drill pipe is a regular circular cross-section, which is conducive to the rapid discharge of cuttings. In the dual drill pipe directional drilling system, the annulus between the outer drill pipe and the borehole wall is blocked at the bore entry pit. The flushing fluid is pumped down the annulus between the outer drill pipe and the inner drill pipe and back up the

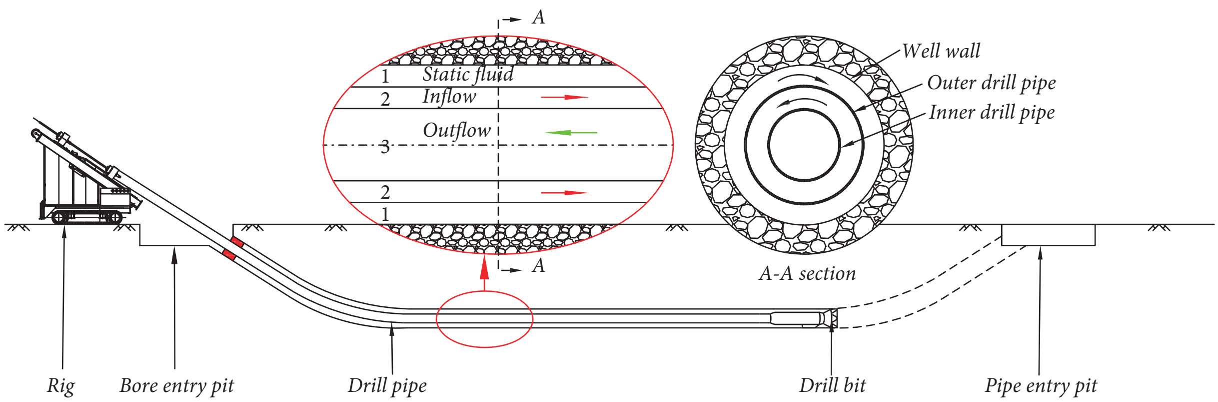


Figure 1: Schematic diagram of the dual drill pipe directional drilling system: in the figure, 1 represents the annulus between the outer drill pipe and the well wall; 2 represents the annulus between the inner drill pipe and the outer drill pipe; 3 represents the center hole of the inner drill pipe.

central hole of the inner drill pipe. This cycle model is defined as the dual drill pipe reverse circulation in this study. The advantage of this cycle model is that not only it can ensure drilling efficiency but also make the annulus between the outer drill pipe and the well wall full of static fluid with pressure, which can effectively maintain the well wall stability.

2.2. Assumptions. The simulation and experiment adopt the following assumptions:

(1) The mud is an incompressible steady fluid, ignoring the boundary effect.

(2) The cuttings are spherical particles with uniform density, and the cuttings do not affect the fluid properties.

(3) The rotation of the inner and outer drill pipes is concentric.

(4) The drill pipe is infinitely thin, regardless of the influence of the drill pipe thickness.

2.3. Simulation

2.3.1. Simulation Model. The simulation model is consistent with the actual drilling tool combination. The model includes the inner drill pipe channel, the inner drill pipe, the annulus between the inner drill pipe and the outer drill pipe, the outer drill pipe, and the annulus between the outer drill pipe and the borehole wall. The computational domain is divided into two parts, the stationary area and the motion area, owing to the need to simulate the rotations of the inner and outer drill pipes. Data are transferred through the interface between the two areas. Figure 2 shows parts of the compositional domain.

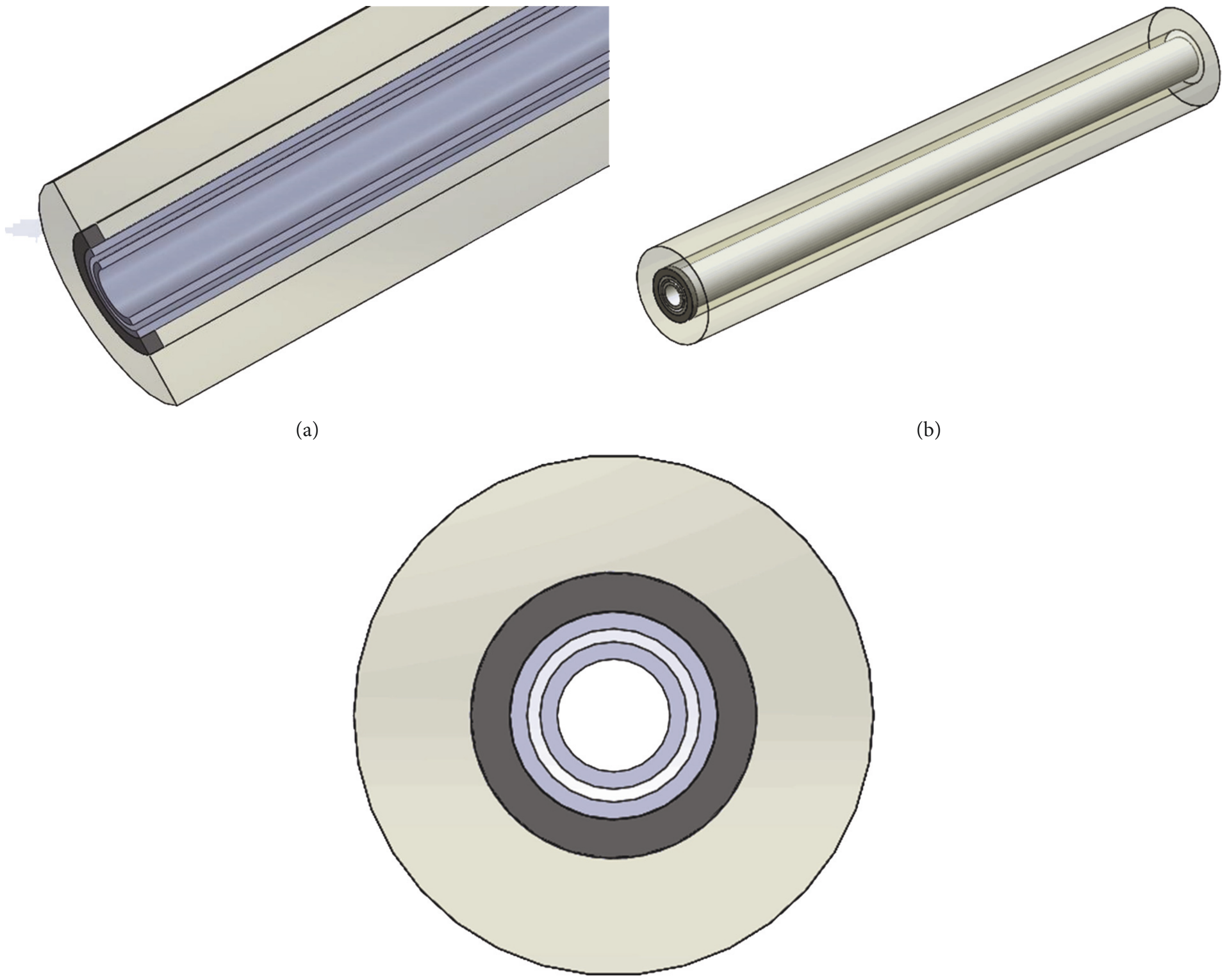
The geometric dimensions of each part are listed in Table 1.

Because the drill pipe is long and the viscosity of fluid has a significant influence on the pressure loss, this study uses boundary layer meshing for the wall surface. The surface is meshed by quadrilateral structural meshes, which are subsequently scanned, resulting in a hexahedral volume mesh. Figure 3 shows the mesh distribution of the boundary layer.

2.3.2. Simulation Parameters. The simulation is transient, and the main parameters considered in the numerical simulation include the inlet flow of the flushing fluid, rotation speed of the drill pipe, and deviation angle of the well. According to field engineering survey data and previous research, the values of the parameters are shown in Table 2.

Three kinds of solid-phase particles (Φ2 mm, Φ6 mm, and Φ10 mm) are selected to simulate the cuttings, all of which have densities of 2500 kg/m^3. According to the distribution of cuttings in the sand cobble stratum, the initial volume fractions of the three kinds of cuttings at the bottom of the borehole are 60% for 2 mm, 30% for 6 mm, and 10% for 10 mm. Considering the momentum equations of each phase separately, the Euler model can obtain accurate results for flow with motions, such as phase-to-phase slip. This model is widely applied in cases with fluidized beds and particle suspension. Using the Euler model, this study achieves the coupling between the phases by pressure and phase-to-phase exchange coefficients.

2.3.3. Mesh Independency Analysis. To make the calculation results accurate and credible, it is necessary to analyze the independence of the mesh. The parameters for mesh independence analysis are inlet flow rate of 2 L/s, drill pipe rotation speed of 40 r/min, and well deviation angle of 80 degrees. The number of meshes increased from 60,000 to 140,000, with an increment of 20,000 per change. The variation of the volume fraction of cuttings in the inner drill pipe with the increase of the number of meshes is shown in Figure 4. From the figure, it can be seen that the calculation results are stable when the number of meshes is greater than 120,000. In this simulation, the number of meshes is 120,000, which can ensure the accuracy of the calculation results.



(a) (b) (c)

Figure 2: Schematic diagram of the geometric model used in the CFD numerical simulation.

Table 1: Specifications of the CFD numerical simulation elements.

Wellbore diameter (mm)	165
Outer diameter of the outer drill pipe (mm)	102
Inner diameter of the outer drill pipe (mm)	92
Outer diameter of the inner drill pipe (mm)	71
Inner diameter of the inner drill pipe (mm)	61
Length of the inner and outer drill pipes (m)	8
Area of the central hole in the inner drill pipe (mm^2)	2920.9
Area of the annulus between the inner and outer drill pipes (mm^2)	2687.0
Area of the annulus between the outer and well wall (mm^2)	13204.4

2.4. Experiment

2.4.1. Experimental Principles and Platform. Figure 5 shows a schematic diagram of the experimental system used for the investigation of cuttings-carrying during reverse circulation drilling with dual concentric pipes. The system considers the existing drilling tool size; thus, the simulation results can be validated. The total length of the test section is 7 m. Custom transparent acrylic tubes with inner diameters of Φ165 mm are used to simulate the borehole. A steel tube with an outer diameter of Φ102 mm and an inner diameter of Φ92 mm is employed to simulate the outer drill pipe. A rope coring drill pipe with an outer diameter of Φ71 mm and an inner diameter of Φ61 mm is used to simulate the inner drill pipe. All tubes are concentric by the inner and outer support rings. The support ring has holes to ensure that flushing fluid can pass. The acrylic tubes are sealed and connected by a flange plate, whereas the inner and outer drill pipes are connected by threads. Rotation of the drill pipe is performed by clamping the two-channel faucet using a variable frequency motor, and varying drilling fluid displacements are achieved by changing the pumping speed of the mud pump. Figure 6 is a physical map and some detailed views of the test system.

2.4.2. Fluid. The flushing fluid is formulated with 6% sodium bentonite, 0.6% sodium carbonate, and 0.3% sodium carboxymethylcellulose (CMC). The viscosity and density of the have a great influence on the cutting-carrying effect. In general, the greater the viscosity of the rinse solution, the stronger the ability to carry cuttings, but the excessive viscosity will cause problems such as high flow resistance

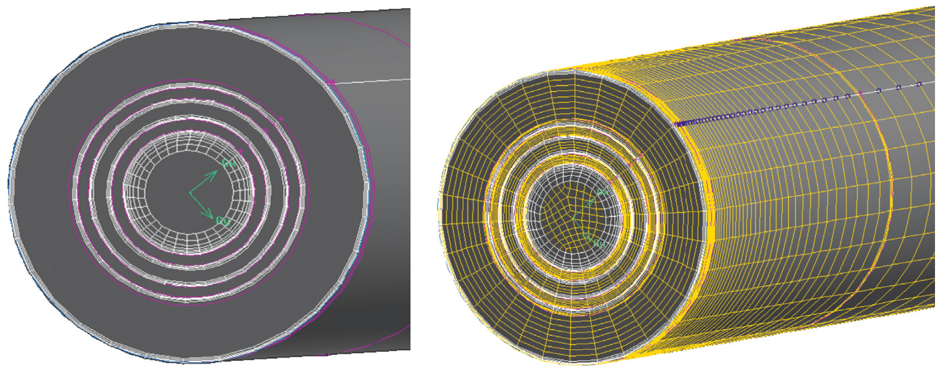


Figure 3: Mesh distribution: (a) the boundary layer mesh distribution, (b) the hexahedral mesh distribution.

Table 2: The values of the three parameters.

Parameters	Unit	Value
Inlet flow rate	L/s	0.5, 1, 2, 5, 10
Rotation speed of the drill pipe	r/min	0, 10, 20, 30, 40, 50, 60, 70, 80
Deviation angle of the well	degrees	70, 80, 90

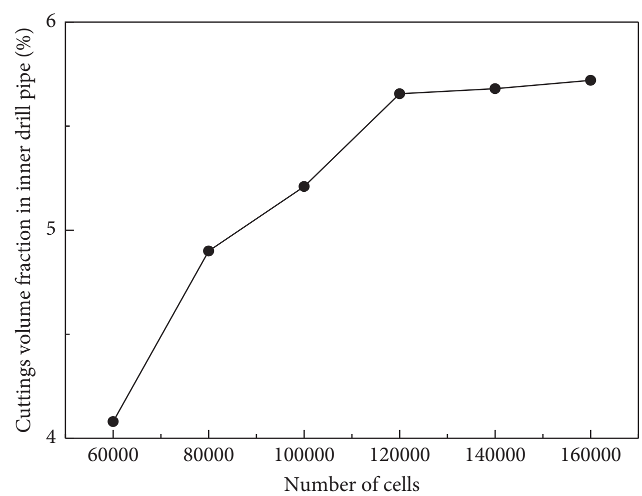


Figure 4: Mesh independence analysis results.

and high pump pressure. The measured viscosity is 30.8 mPa·s, and the density is 1026 kg/m^3. The Herschel–Bulkley parameters of the flushing fluid obtained by the specific gravity scale and the rheometer are shown in Table 3. Comparing the data calculated by the Herschel-Bulkley model with the data measured by the rheometer is shown in Figure 7. According to research by Sayindla et al. [25], the shear rate of the flow loop is below 400 s^{-1}. It can be seen from Figure 7 that the data calculated by the Herschel-Bulkley model agree well with the experimentally measured data when the shear rate is lower than 400. Therefore, it can be considered that the rinsing liquid of this experiment is a Herschel-Bulkley model.

The variation range of the flushing fluid parameters during the experiment is shown in Table 4. It can be seen from the table that the flow velocity in the inner drill pipe is close to that in the annulus, but the Reynolds number of the inner drill pipe is more than twice that of the annulus. When the inlet flow rate is 3 L/s and 5 L/s, the Reynolds number in the inner drill pipe exceeds 2000, so the fluid is in a turbulent state.

2.4.3. Cuttings. Green glass beads are used to represent the cuttings (Figure 8); the density is 2540 kg/m^3. The specifications are identical to the cuttings in the simulation. Before each experiment, 10 kg of glass beads having a diameter of 2 mm and 5 kg of glass beads having a diameter of 6 mm were uniformly mixed. This results in the same volume fraction of glass beads at the bottom of the well as the simulated volume.

The experimental steps are as follows:

(1) Mix the flushing fluid and load the glass beads into the sand bucket.

(2) Turn on the mud pump, inject the flushing fluid into the loop with low displacement, discharge the air in each annulus and establish a cycle.

(3) Turn on the motor to rotate the drill pipe at a certain speed.

(4) Maintain a constant flow rate, open the sand bucket valve to inject the glass beads, and circulate until no glass beads flowing out from the outlet.

(5) Close the sand bucket valve, and load 15 kg of mixed glass beads into the sanding bucket.

(6) Adjust the rotating speed and displacement to the set value. After stabilization, open the sanding bucket valve and collect the glass beads at the outlet.

(7) Cycle until the outlet no longer has a glass ball discharged.

(8) Change the parameters and repeat steps 5, 6, and 7 for the next set of tests.

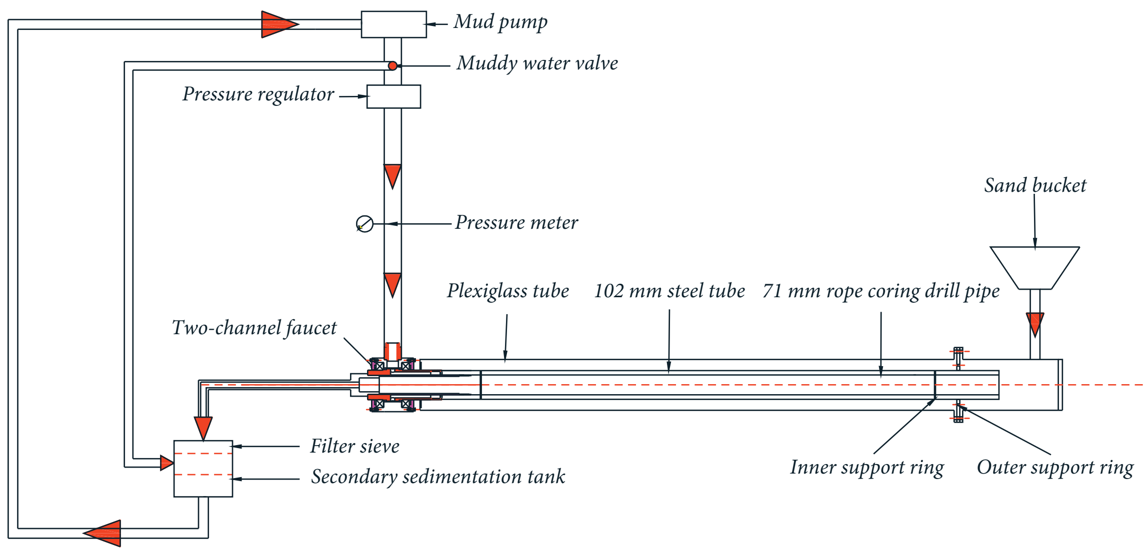
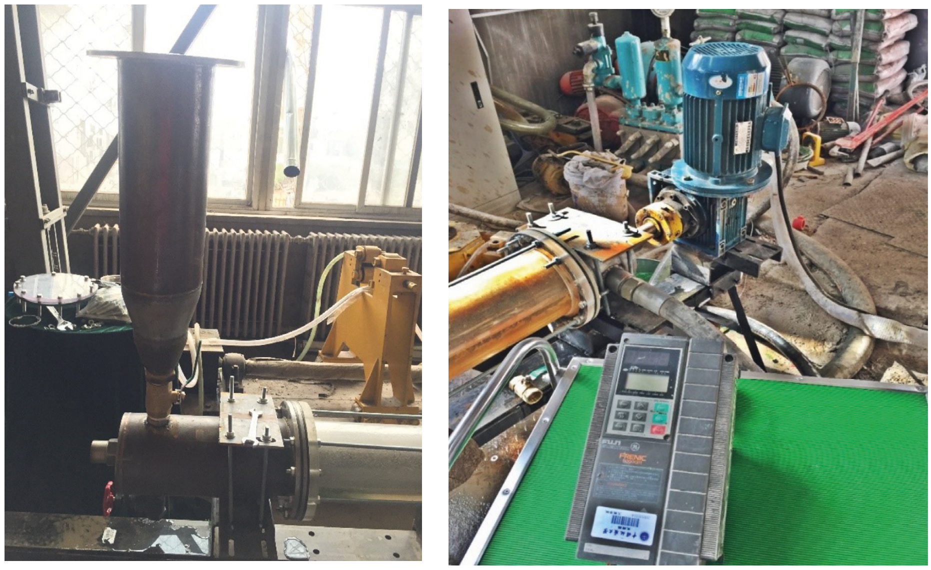


Figure 5: Schematic of the experimental system used to investigate cuttings-carrying during reverse circulation drilling with dual concentric pipes.

(a)

Figure 6: Continued.



(b) (c)

Figure 6: The experimental system used to investigate cuttings-carrying during reverse circulation drilling with dual concentric pipes: (a) Horizontal test section; (b) Sand bucket; (c) Motor and frequency converter for driving the rotation of the drill pipe.

Table 3: Herschel-Bulkley parameter values of the flushing fluid.

Property	K (Pa·s)	n	τ_y (Pa)	Specific gravity (N·cm^3)
Value	0.325	0.66	8.3	1.026

To ensure the accuracy of the test, before changing the parameters for a new test, the next set of displacements is used to cycle until no glass beads are discharged.

The volume fraction of cuttings in the annulus is calculated by the following formula:

$$V_c = \left(\frac{15 - W_d}{\rho_g \times V_a}\right)100\%, \tag{1}$$

where V_c is the average volume fraction of cuttings in the annulus, %; W_d is the mass of the glass beads discharged at the end of the cycle, kg; ρ_g is the density of the glass beads, the value of this test is 2540 kg/m^3; V_a is the volume of the inner drill pipe, the value of this test is 0.02045 m^3.

3. Results and Discussion

3.1. Simulation Results. The influence of drill pipe rotation speed, flushing fluid flow rate, well-deviation angle, and cuttings diameter on the cuttings-carrying was analyzed by simulation data. In the simulation, the initial volume fraction of different diameter cuttings is different, 60% for 2 mm cuttings, 30% for 6 mm cuttings, and 10% for 10 mm cuttings. Therefore, the influence of the diameter of the cuttings on the cuttings-carrying cannot be directly evaluated by the residual volume fraction of the cuttings in the annulus. In this paper, the parameter of cuttings discharge rate C_d is introduced to measure the difficulty of cuttings discharge with different diameters. The value of C_d is between 0 and 1. The larger the value, the easier the cuttings are to be discharged.

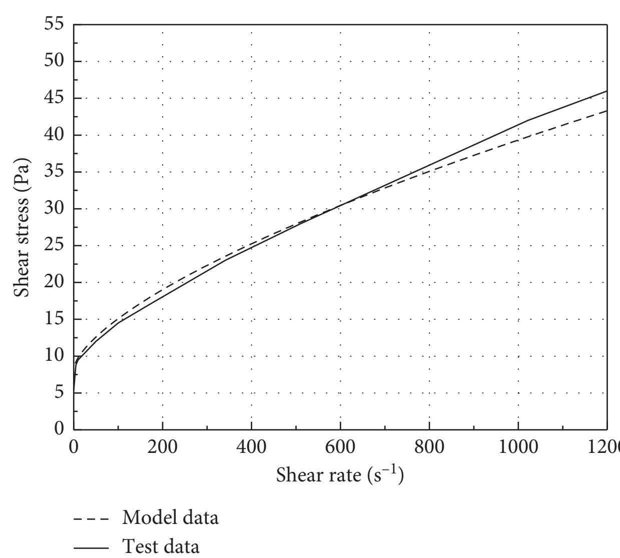


Figure 7: The flow curves calculated by the HB model and the measured.

The definition of cuttings discharge rate is

$$C_d = 1 - \frac{V_s}{V_i}, \tag{2}$$

where C_d is the cuttings discharge rate; V_s is the average volume fraction of cuttings in inner drill pipe at the end of simulation, %; V_i is the volume fraction of cuttings in the annulus at the beginning of simulation, %.

3.1.1. Influence of Rotation Speed of the Drill Pipe on Cuttings-Carrying. The volume fractions of cuttings with different diameters under different rotational speeds, displacement

Table 4: Flow parameters of the flushing fluid during the experiment.

Parameters	Value				
Inlet flow rate ($L \cdot s^{-1}$)	0.5	1	2	3	5
Flow rate of the central hole in the inner drill pipe ($m \cdot s^{-1}$)	0.17	0.34	0.68	1.02	1.7
Reynolds number in the inner drill pipe	345	690	1380	2070	3450
Flow rate of the annulus between the inner and outer drill pipe ($m \cdot s^{-1}$)	0.18	0.36	0.72	1.08	1.8
Reynolds number between the inner and outer drill pipes	126	252	504	756	1260

(a) (b)

Figure 8: Green glass beads used in the experiment: (a) Φ2 mm diameter, and (b) Φ6 mm diameter.

conditions and well deviation angles (70°, 80°, and 90°) are orthogonally analyzed (Figure 9).

As mentioned before, the initial volume fraction of cuttings is 60% for 2 mm, 30% for 6 mm, and 10% for 10 mm. It can be seen from Figure 9 that as the flow rate of the flushing fluid increases, the volume fraction of the cuttings in the inner drill pipe becomes less and less sensitive to the rotational speed of the drill pipe. When the flow rate is greater than 1 L/s, the volume fraction of the cuttings almost no longer changes with the drill pipe rotation speed. When the flow rate is low, the flushing fluid cannot fully agitate the cuttings, which tend to cause the cuttings to deposit on the lower side of the drill pipe. The rotation of the drill pipe will cause the cuttings to rotate together, which prevents the cuttings from being deposited on the lower side of the drill pipe. Therefore, the rotation of the drill pipe can enhance the effect of cuttings-carrying, especially at a low flow rate. When the flow rate is increased, the flushing fluid can stir the cuttings, and the effect of the drill pipe rotation is no longer obvious, so the cuttings volume fraction no longer decreases with the increase of the rotating speed. It is concluded that the rotational speed of the drill pipe is a secondary factor affecting the volume fraction of the cuttings compared to the flow rate. The volume fraction of cuttings in the hole during horizontal directional drilling is determined by the flow rate of the flushing fluid.

3.1.2. Influence of Well Deviation Angle and Cuttings Diameter on Cuttings-Carrying. The volume fractions of cuttings with different diameters in wells with different deviation angles at a rotational speed of 40 r/min and inlet flow rate of 5 L/s are compared and analyzed. A larger cuttings discharge means that the cuttings are more easily carried by the drilling fluid.

Figure 10(a) shows the influences of the well deviation angle and cuttings diameter on the volume fractions of cuttings at high rotational speed (40 r/min) and high inlet flow rate (5 L/s). Figure 10(b) shows the influences of the well deviation angle and cuttings diameter on the volume fractions of cuttings at low rotational speed (0 r/min) and low inlet flow rate (1 L/s). From the data in Figure 10, it is known that the cuttings volume fraction at low flow rates is 7 to 10 times that at high flow rates. This again proves that the flushing fluid flow rate is the determining factor affecting the cuttings volume fraction.

Figure 11 shows the relationship between the discharge rate (C_d) of different diameter cuttings and the inclination angle of the well under these two conditions. The cuttings discharge rates under high rotation speed (40 r/min) and high flow condition (5 L/s) are significantly higher than that under low rotation speed (0 r/min) and low flow condition (1 L/s). The change of the well deviation angle at the high flow rate (5 L/s) has little effect on the cuttings discharge rate. However, when the flow rate is low (1 L/s), the cuttings discharge rate increases as the well deviation angle increases.

Cuttings with a diameter of 6 mm are the easiest to be discharged, and the cuttings with the diameter of 10 mm are the most difficult to be discharged under these two conditions. The difficulty of discharging 2 mm cuttings is between 6 mm and 10 mm cuttings. For cuttings with the diameter of 10 mm, gravity is relatively large, so it is more difficult to be

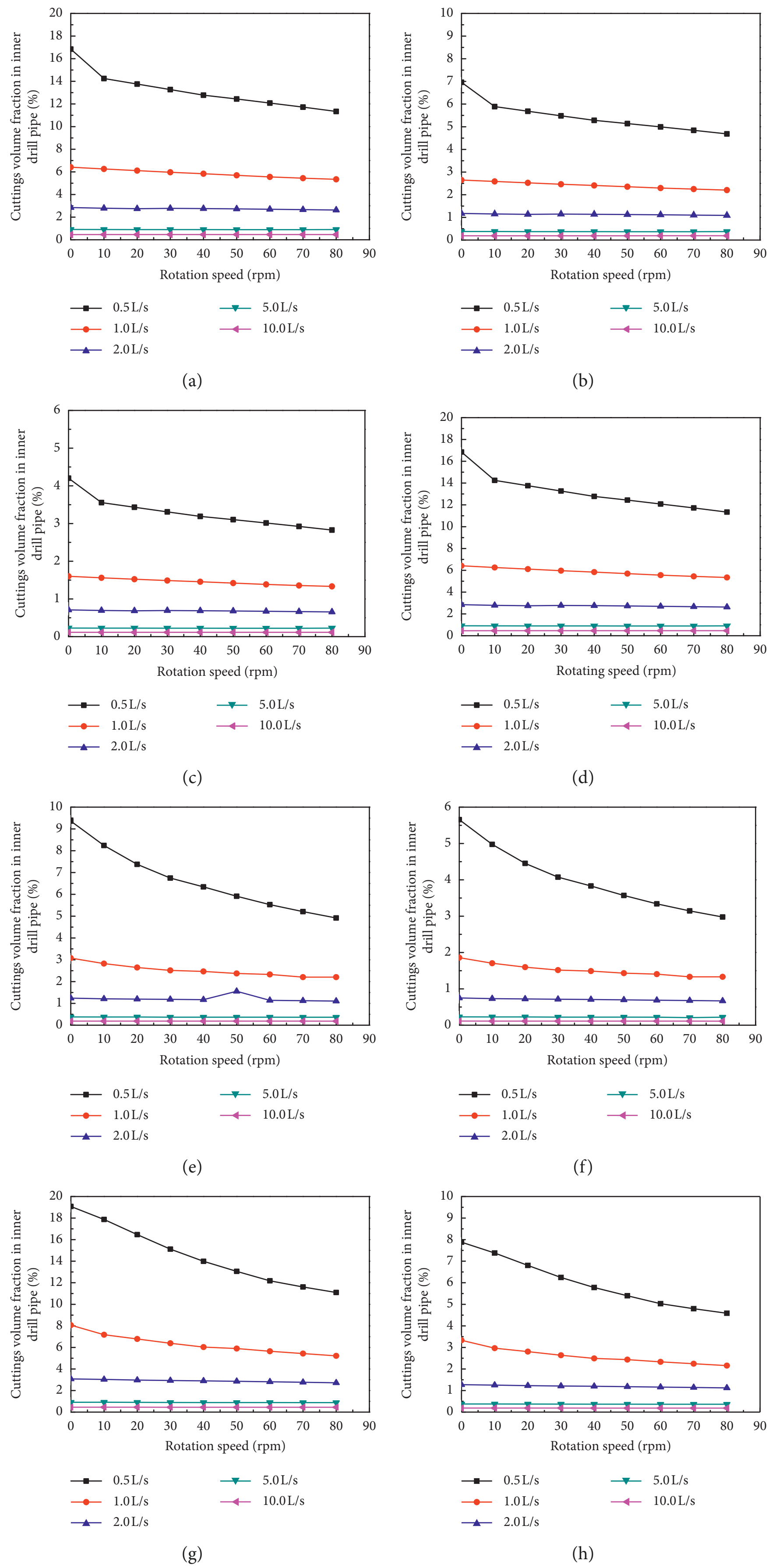
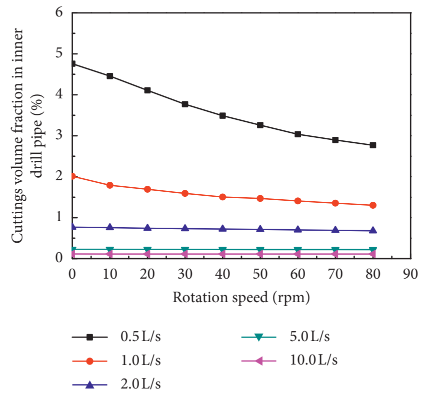
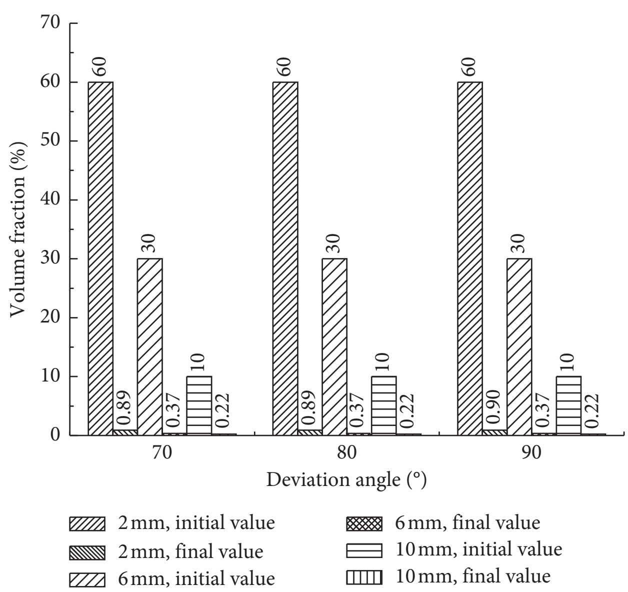


Figure 9: Continued.

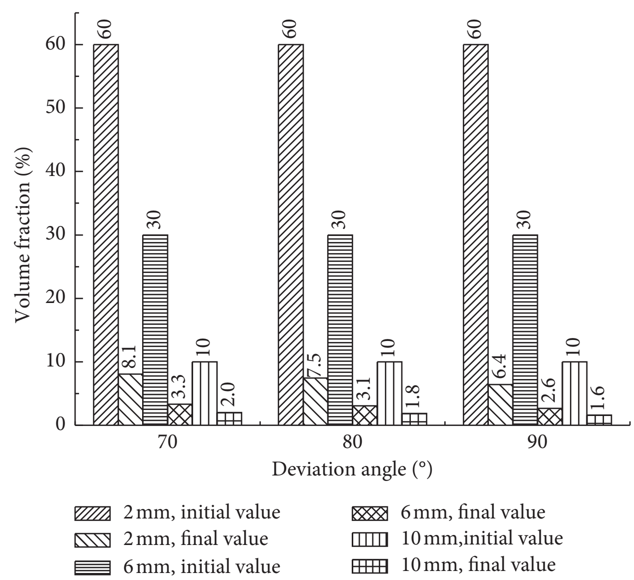


(i)

FIGURE 9: Volume fractions of cuttings with different diameter at the bottom of the drill tool under different rotational speeds: (a) well deviation angle is 90 degrees and cuttings diameter is 2 mm, (b) well deviation angle is 90 degrees and cuttings diameter is 6 mm, (c) well deviation angle is 90 degrees and cuttings diameter is 10 mm, (d) well deviation angle is 80 degrees and cuttings diameter is 2 mm, (e) well deviation angle is 80 degrees and cuttings diameter is 6 mm, (f) well deviation angle is 80 degrees and cuttings diameter is 10 mm, (g) well deviation angle is 70 degrees and cuttings diameter is 2 mm, (h) well deviation angle is 70 degrees and cuttings diameter is 6 mm, and (i) well deviation angle is 70 degrees and cuttings diameter is 10 mm.



(a)



(b)

FIGURE 10: Influences of the well deviation angle and cuttings diameter on the volume fraction of cuttings: (a) under high rotational speed (40 r/min) and high inlet flow rate (5 L/s) conditions; (b) under low rotational speed (0 r/min) and low inlet flow rate (1 L/s) conditions.

discharged. For the cuttings with the diameter of 2 mm, it is more difficult to be discharged because of the low viscosity of the flushing fluid and the weak suspension ability of the cuttings particles.

3.2. Experimental Results. Using the test platform introduced in Section 2, the cuttings-carrying experiment with 90 degrees of well deviation is carried out. A total of 35 sets of tests were carried out under the conditions of changing the rotational speed of the drill pipe and the inlet flow rate. The results are shown in Table 5. In the table, the volume fraction of cuttings in the inner drill pipe is the sum of the volume fractions of cuttings of 2 mm and 6 mm.

Figure 12 is drawn from the data in Table 5. It can be seen from Figure 12 that the cuttings volume fraction decreases rapidly as the flushing fluid flow rate increases. However, when the displacement is greater than 2 L/s, the cuttings volume fraction decreases slowly. This means that under such a bottom hole assembly, as long as the flushing fluid flow rate is greater than 2 L/s, most of the cuttings can be carried. To achieve a better cuttings-carrying effect, the Reynolds number of the flushing fluid in circulation channel

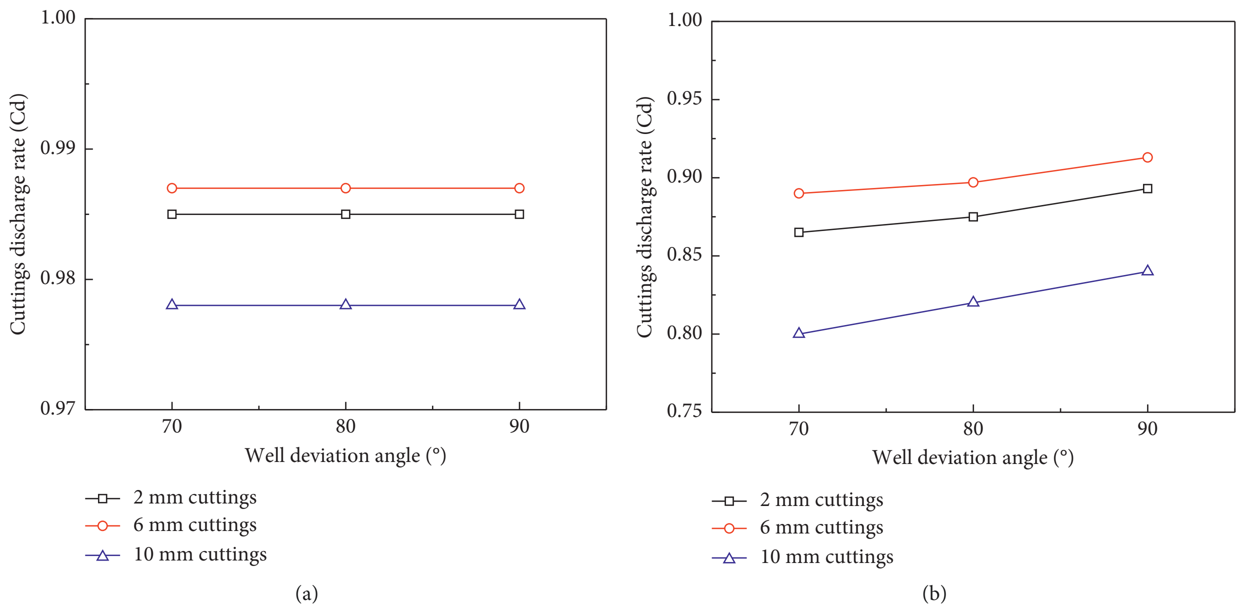


FIGURE 11: Influences of the well deviation angle and cuttings diameter on the cuttings discharge rate: (a) under high rotational speed (40 r/min) and high flow rate (5 L/s) conditions, and (b) under low rotational speed (0 r/min) and low flow rate (1 L/s) conditions.

TABLE 5: Summary of experimental results.

Rotation speed of drill pipe (r/min)	Inlet flow rate (L/s)	Discharge quality of cuttings (kg)	Volume fraction of cuttings in inner drill pipe (%)
0	0.5	1.91	25.00
	1.0	8.21	12.97
	2.0	12.51	4.76
	3.0	12.98	3.86
	5.0	13.92	2.06
10	0.5	4.23	20.57
	1.0	10.18	9.21
	2.0	11.67	6.36
	3.0	11.85	6.02
	5.0	14.12	1.68
20	0.5	4.31	20.42
	1.0	10.24	9.09
	2.0	12.23	5.29
	3.0	11.32	7.03
	5.0	14.21	1.51
30	0.5	4.78	19.52
	1.0	10.42	8.75
	2.0	12.43	4.91
	3.0	13.54	2.79
	5.0	14.12	1.68
40	0.5	4.32	20.40
	1.0	10.62	5.79
	2.0	12.21	5.33
	3.0	12.40	4.97
	5.0	13.97	1.97
50	0.5	3.80	21.39
	1.0	7.21	14.88
	2.0	12.96	3.90
	3.0	12.21	5.33
	5.0	14.19	1.55
60	0.5	3.70	21.58
	1.0	8.50	12.42
	2.0	12.30	5.16
	3.0	12.40	4.97
	5.0	14.30	1.34

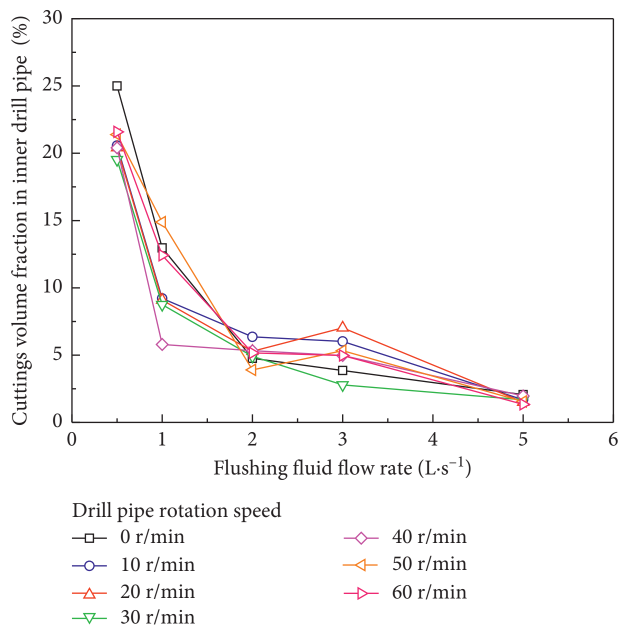


Figure 12: Experimental results of dual drill pipes reverse circulation.

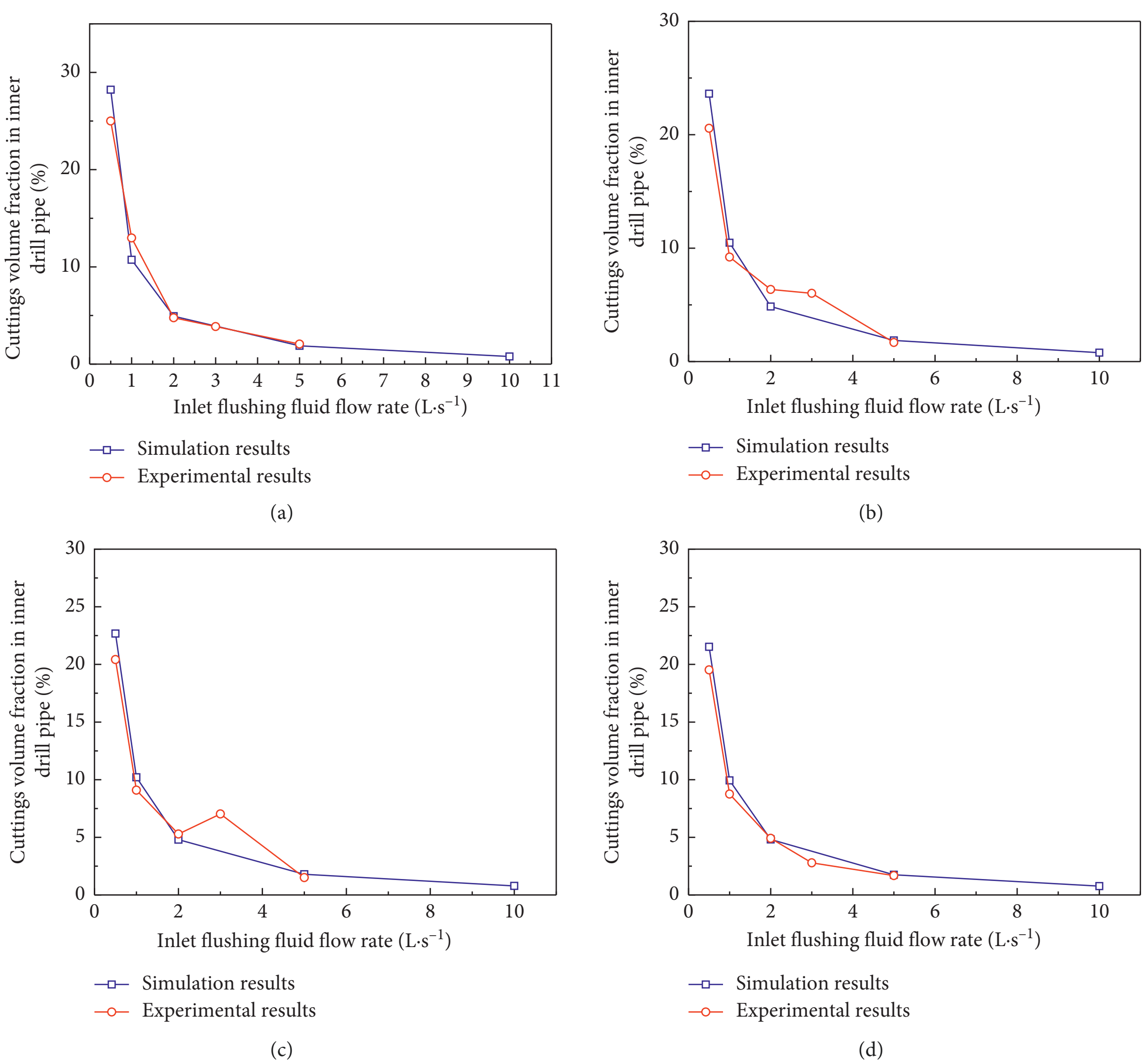


Figure 13: Continued.

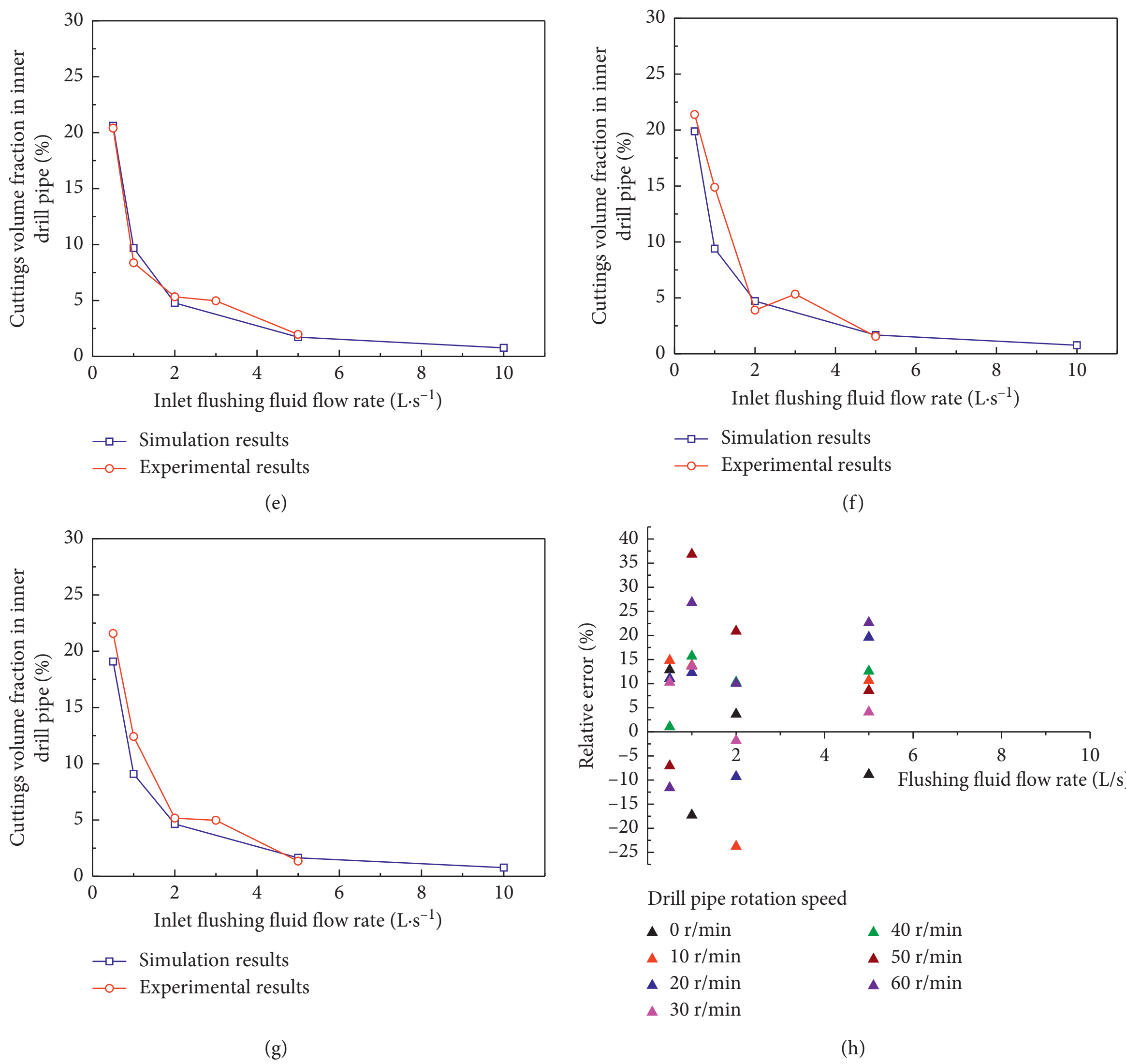


FIGURE 13: Comparison of simulation results and experimental results when the inclination angle is 90 degrees: (a) rotation speed is 0; (b) rotation speed is 10 r/min; (c) rotation speed is 20 r/min; (d) rotation speed is 30 r/min; (e) rotation speed is 40 r/min; (f) rotation speed is 50 r/min; (g) rotation speed is 60 r/min; (h) the distribution of relative errors.

should be greater than 1380. However, when the Reynolds number exceeds 2000 (3 L/s), the flushing fluid changes from laminar flow to a turbulent flow which is not conducive to the discharge of cuttings. From the experimental results, it can be seen that when the flow rate increases from 2 L/s to 3 L/s, the cuttings volume fraction does not decrease significantly. The same as the simulation results, the rotation speed of the drill pipe has little effect on the cuttings volume fraction.

3.3. Comparison and Analysis of Simulation Results and Experimental Results. To verify the accuracy of the simulation model, the simulation results were compared with the experimental results. Since there were no glass beads with a diameter of 10 mm during the experiment, only the results of the comparison of the diameters of 2 mm and 6 mm were performed.

In Figure 13, Subgraph (a) to Subgraph (g) shows the relationship between simulation and experimental results at different rotational speeds. Subgraph (h) shows the error distribution. It can be seen from Figure 13 that the simulation results are in good agreement with the experimental results except for individual points, and the relative errors between the simulation results and the experimental results are within 20%. The error at high speed is greater than the error at low speed.

4. Conclusions

In this paper, the law of cuttings migration of HDD with dual drill pipe is studied by experiments and simulations. The following conclusions are listed:

(1) The first experimental system for investigations of cuttings-carrying in reverse circulation drilling with dual drill pipes is designed and built, and a cuttings-

carrying model for reverse circulation drilling with dual drill pipes is established.

(2) Through simulation and experimental results, it is found that the flushing fluid flow rate is the main factor affecting the cuttings discharge, and the drill pipe rotation speed and the well angle are secondary factors. Ensuring that the Reynolds number is greater than 1380 during horizontal directional drilling can effectively reduce the cuttings volume fraction in the hole. For the tool structure proposed in this study, when the flow rate of the flushing liquid is more than 2 L/s, the volume fraction of the cuttings in the hole is about 5%, which can meet the requirements of safe drilling.

(3) The experimental results are in good agreement with the simulation results, and the accuracy of the simulation results is verified.

Nomenclature

K: The consistency index, Pa·s^n
n: The flow index
τ_y: Yield stress, Pa
V_c: The average volume fraction of cuttings in the annulus, %
W_d: The mass of the glass beads discharged at the end of the cycle, kg
ρ_g: The density of the glass beads, kg/m^3
V_a: The volume of the inner drill pipe, m^3
C_d: The cuttings discharge rate
V_s: The average volume fraction of cuttings in the inner drill pipe at the end of simulation, %
V_i: The volume fraction of cuttings in the annulus at the beginning of simulation, %.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interests regarding the publication of this paper.

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References

[1] ASTM, *Standard Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit under Obstacles, Including River Crossings*, American Society for Testing Materials, West Conshohocken, PA, USA, 1962.

[2] Driscopipe, "Technical expertise: application of Driscopipe in directional drilling and river crossings," *Technical Note*, vol. 41, pp. 1–40, 1993.

[3] S. Yu, Z. Duan, Y. Liu, M. Ma, and S. Ma, "Estimating the effects of tunnelling on preexisting jointed pipelines," *Advances in Civil Engineering*, vol. 2019, Article ID 1643594, 12 pages, 2019.

[4] P. Zhang, L. Jin, X. Du, and D. Lu, "Computational homogenization for mechanical properties of sand cobble stratum based on fractal theory," *Engineering Geology*, vol. 232, pp. 82–93, 2018.

[5] T. Feng, Y. Tang, Q. Wang, J. Zhang, and J. Song, "Experimental investigation of dynamic characteristics of subsea sand-silt mixtures," *Advances in Civil Engineering*, vol. 2019, Article ID 5619039, 9 pages, 2019.

[6] Y. Lin, Y. Lv, X. Liu, and F. Chen, "Analysis of longitudinal mechanical properties of buried suspended pipeline resisting collapse," *Advances in Civil Engineering*, vol. 2019, Article ID 3954390, 10 pages, 2019.

[7] T. Xu, D. Pei, L. Huang, and Z. Yan, "Analysis and countermeasure about common downhole problem in extended-reach well," *Drilling and Production Technology*, vol. 24, no. 5, pp. 22–25, 2001.

[8] M. Duan, S. Z. Miska, M. Yu, N. E. Takach, R. M. Ahmed, and C. M. Zettner, "Transport of small cuttings in extended-reach drilling," *SPE Drilling & Completion*, vol. 23, no. 3, pp. 258–265, 2008.

[9] A. Ramadan, P. Skalle, S. T. Johansen, J. Svein, and A. Saasen, "Mechanistic model for cuttings removal from solid bed in inclined channels," *Journal of Petroleum Science and Engineering*, vol. 30, no. 3-4, pp. 129–141, 2001.

[10] J. Ogunrinde and A. Dosunmu, "Hydraulics optimization for efficient hole cleaning in deviated and horizontal wells," in *Proceedings of the 2012 Nigerian Annual International Conference and Exhibition*, Abuja, Nigeria, August 2012.

[11] R. B. Adari, S. Miska, E. Kuru, P. Bern, and A. Saasen, "Selecting drilling fluid properties and flow rates for effective hole cleaning in high-angle and horizontal wells," in *Proceedings of the 2000 SPE Annual Technical Conference and Exhibition in Dallas*, Dallas, TX, USA, October 2000.

[12] T. Nazari, G. Hareland, and J. Azar, "Review of cuttings transport in directional well drilling: systematic approach," in *Proceedings of the SPE Western Regional Meeting*, Anaheim, CA, USA, May 2010.

[13] Z. Zhang, Q. Li, and H. Yan, ""Two speeds" on hole cleaning efficiency of high-angle well," *Petrochemical Industry Application*, vol. 29, pp. 9–13, 2010.

[14] J. Chen, X. Liu, and G. Ding, "Experimental research on cuttings-carrying in the annulus of a horizontal well section," *Journal of China University of Petroleum*, vol. 16, pp. 23–26, 1992, in Chinese.

[15] M. E. Ozbayoglu, M. Sorgun, A. Saasen, and K. Svanes, "Hole cleaning performance of light-weight drilling fluids during horizontal underbalanced drilling," *Journal of Canadian Petroleum Technology*, vol. 49, no. 4, pp. 21–26, 2010.

[16] E. M. Ozbayoglu, A. Saasen, M. Sorgun, and K. Svanes, "Effect of pipe rotation on hole cleaning for water based drilling fluids in horizontal and deviated wells," in *Proceedings of the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition*, Jakarta, Indonesia, August 2008.

[17] X. Sun, "Experimental research on cuttings transport in highly-deviated well sections and the design and optimization of hole cleaning tools," Ph.D. thesis, China University of Geosciences (Beijing), Beijing, China, 2014.

[18] M. Zamora and P. Hanson, “Rules of thumb to improve high-angle hole cleaning,” *Petroleum Engineer International*, vol. 63, no. 1, pp. 44–51, 1991.

[19] S. Okranji, “Mud cuttings transport study in directional well drilling,” Ph.D. thesis, University of Tulsa, Tulsa, OK, USA, 1981.

[20] J. Li and S. Walker, “Sensitivity analysis of hole cleaning parameters in directional wells,” in *Proceedings of the SPE/ICoTA Coiled Tubing Roundtable Conference*, Houston, TX, USA, May 1999.

[21] S. Akhshik, M. Behzad, and M. Rajabi, “CFD-DEM simulation of the hole cleaning process in a deviated well drilling: the effects of particle shape,” *Particuology*, vol. 25, pp. 72–82, 2016.

[22] O. M. Vestavik, M. O. Meling, and S. E. Meinseth, “Casing drilling system and method,” US Patent US20150322721A1, 2017.

[23] O. M. Vestavik and H. Syse, “Down hole well tool with expansion tool,” US Patent US8925629B2, 2015.

[24] O. M. Vestavik and H. Syse, “Mud lift pump for dual drill string,” US Patent US20150027781A1, 2015.

[25] S. Sayindla, B. Lund, J. D. Ytrehus, and A. Saasen, “Hole-cleaning performance comparison of oil-based and water-based drilling fluids,” *Journal of Petroleum Science and Engineering*, vol. 159, pp. 49–57, 2017.


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