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The Numerical and Experimental Research on Solid-Liquid Two-Phase Flow Pattern in the PID

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ABSTRACT
Particle impact drilling (PID) technology can effectively improve the speed of drilling in deep and hard formations. It is important to study the particle flow pattern in the annulus since it can ensure the smooth implementation of PID. In this paper, experimental and numerical methods are used to study the law of motion in the annulus. This study finds that the distribution of particles in the annulus is uneven, and the particle settling velocity is hardly affected by the fluid density, fluid velocity, particle volume concentration. Particle settling velocity decreases with the increasing of drilling fluid viscosity, but increases with the increasing of the particle diameter. On this basis, the reasonable parameters of the drilling fluid for PID are obtained.

Key words: Petroleum engineering; Particle impact drilling; Solid-liquid two-phase flow

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INSTRUCTION

Particle impact drilling (PID) technology is a new oil drilling technology, designed for the development of oil and gas resources in deep and highly abrasive formations. PID refers to adding steel particles, the diameter of which is 1-3 mm, to the volume concentration of 1%-3% into the drilling fluid during the conventional rotary drilling to break rocks through bit nozzles by high frequency jet. This technology plays the role of a secondary rock breaking, thus significantly improves the penetration rate and accelerates the production of oil and gas wells.

Currently, this technology is in theoretical research and experimental stage in China. By studying PID prospects for practical application in China, XU Yi-Ji et al.[1−2] develop the first set of the complete PID system in China. Only U.S. companies PDTI (Particle Drilling Technologies, Inc)[3-5] conducted field tests in the hard wearing formations in Utah and eastern Texas in North America. Their results show that drilling speed increased by 3 to 4 times under the same conditions. Therefore, PID enjoys enormous potentials in accelerating the drilling of deep wells and hard formations. The technology has broad application prospects in western Sichuan Province, China, which has abundant resources of oil and gas buried deep in areas which feature hardness and abrasive resistance.

The back flow of particles and drilling mud in the wellbore annulus can be viewed as solid-liquid two-phase flow. As the density of the steel particles is greater than that of the particles produced by conventional drilling cuttings, the flow pattern is different from conventional drilling fluid carrying the cuttings to the ground. If the fluid particles can not be brought back to the ground, it may lead to particle deposition in the wellbore, causing sticking and other accidents, even fracture of the formation with the fluid density increasing by the particle deposition. Therefore, the particle and fluid phase flow pattern in the wellbore annulus is crucial to the success of the PID technology.

1. NUMERICAL SIMULATION OF PARTICLE MOTION LAW IN DRILLING FLUID

1.1 Modeling and Parameters Selection

Assume both the outer wall of drill pipe and the inner wall of the borehole are smooth, the drill pipe and the annulus axial eccentricity is zero, and ignore the rotation of the drill pipe. It requires relatively shorter time and distance for the particles to enter into annulus and stabilize. Therefore, to meet full development of the solid-liquid two-phase flow in the annulus, the length of model is taken as 4 m. The boundary condition at inlet is velocity; the boundary condition at outlet is free outlet, provided the fluid and the particles have the same initial velocity. As drilling fluid in the annulus boundary velocity is zero, the boundary is set to no-slip boundary, using the wall function method.

Boundary conditions and parameters are chosen as follows in Table 1. Annulus 3D model and inner meshed flow field are as shown in Figure 1.

Table 1
Calculation Parameters

Particle diameter mm	Particle density g/cm^3	Particle volume concentration %	Drilling fluid velocity m/s	Drilling fluid density g/cm^3	Drilling fluid viscosity mPa·s	Annulus outer diameter mm	annulus internal diameter mm
1	7.8	1	0.9	1.1	25	210	114
1.7		2	1.05	1.23	40		
2		3	1.2	1.36	55		

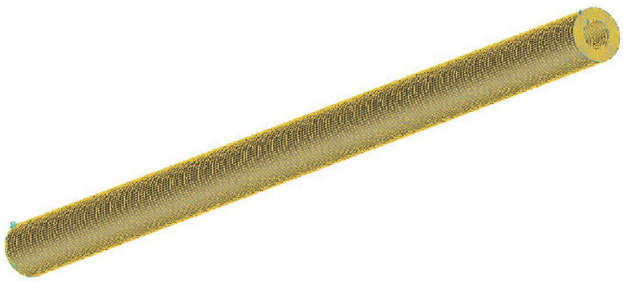

Figure 1
Diagram of the Meshed Annulus Model

1.2 Analysis of Simulation Results

1.2.1 The Particle Volume Concentration in the Distribution of the Annulus Section

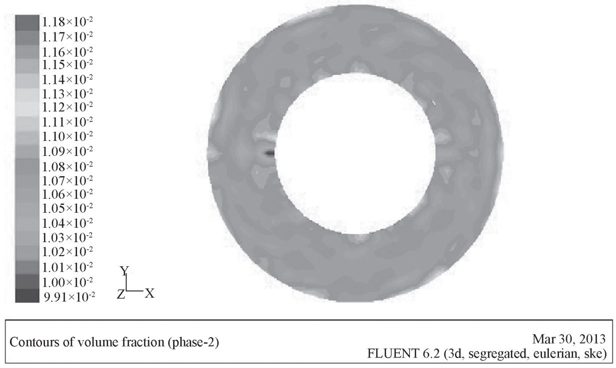

Figure 2
Particle Volume Fraction Contour of a Cross Section

As shown in Figure 2, particles are unevenly distributed in the annulus. Overall, the volume concentration of particles is larger than that of near the wall.

The high drilling fluid viscosity is caused by the particle concentration, leading to the decreasing of particle velocity. And the velocity is fast in the areas of lower particles concentration. Relative motion is occurred between the areas of higher particle concentration and lower concentration, prompting the district to be shear failure. Particles are mixed together, causing the uneven particle volume concentration in the region, and the particle volume concentration is different in the same area at different times.

1.2.2 Drilling Fluid Density Effect on the Particle Settling Velocity

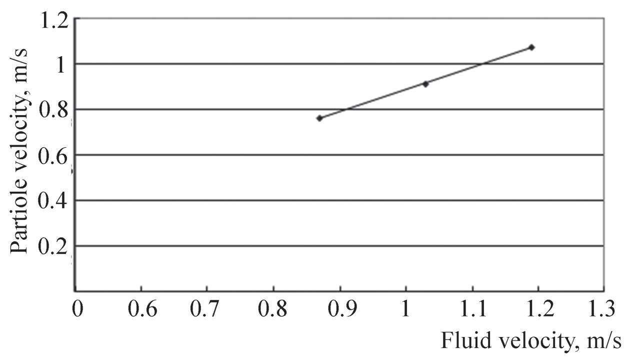

Figure 3
Relationship Between Particle Settling Velocity and the Fluid Density

In Figure 3, with the increasing of fluid density, the speed of particle sedimentation decreases gradually. This is good for the fluid to carry particles. But the amplitude of the particle settling velocity decreases with the drilling fluid density is small, due to the great difference between the density of the drilling fluid and particles. The density increasing of fluid in small ranges can not significantly reduce the difference of density between the drilling fluid and particle.

1.2.3 Drilling Fluid Velocity Effect on the Particle Settling Velocity

In Figure 4, as the fluid velocity increases, the particle velocity increases. It is approximate linear relationship between the two variables. However, the particle settling velocity values in the drilling fluid change little with the increasing of the velocity of drilling fluid.

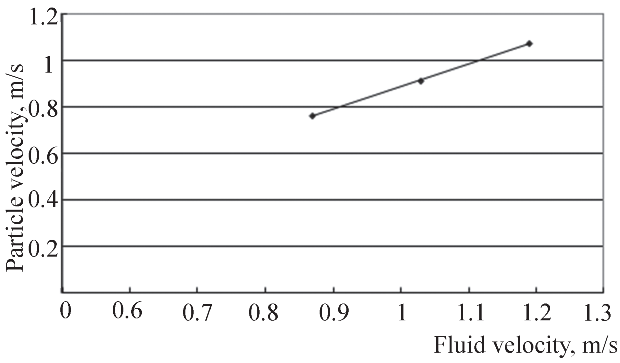

Figure 4
Relationship Between Drilling Fluid Velocity and Particle Velocity

1.2.4 Drilling Fluid Viscosity Effect on the Particle Settling Velocity

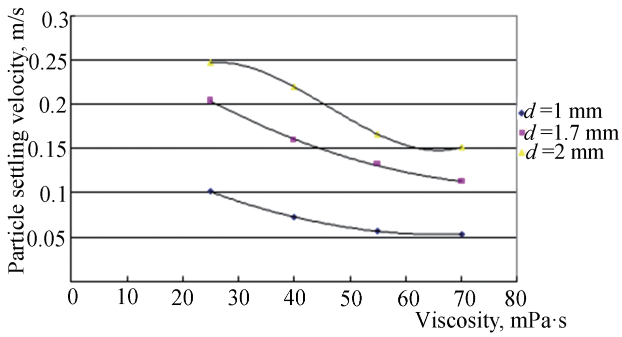

Figure 5
Relationship Between Particle Settling Velocity and Drilling Fluid Viscosity

As shown in Figure 5, with the increasing of fluid viscosity, the velocity of particles decreases gradually. This is because with the increasing of the viscosity of the drilling fluid, consistency coefficient increases as well. If the shear rate is constant, fluid shear stress on the particles increases gradually, making it easier to carry the gravity particles back.

The settling velocity of the particles in three kinds of diameters are relatively small. Even if the fluid viscosity is 25 mPa·s, the settling velocity of the particles are less than 0.25 m/s. when the fluid viscosity is 70 mPa·s, the settling velocity of the particles are less than or equal to 0.15 m/s, with high particles lift efficiency.

1.2.5 Particle Diameter Effect on the Particle Settling Velocity

In Figure 6, the settling velocity of particles in drilling fluid increases in line with the particle diameter. This is because with the increasing of the particle diameter, the gravity of particles increases. In addition, the change of the particle diameter can also cause changes in flow patterns around, and thus the settling velocity of particles in drilling fluid is affected.

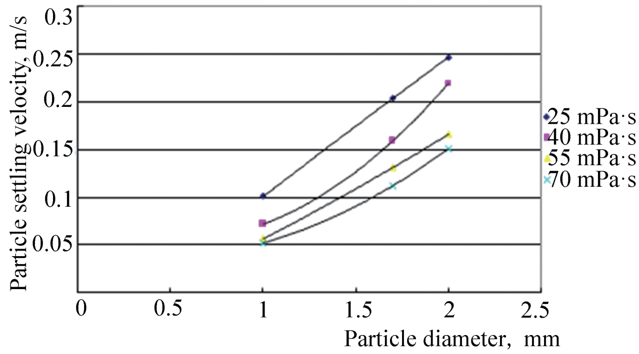

Figure 6
The Curve of Particle Settling Velocity and Particle Diameter

1.2.6 Particle Volume Concentration Effect on the Particle Settling Velocity

In Figure 7, when the particle volume concentration is 1% to 3%, the particle settling velocity decreases with the increasing of particle volume concentration, that is the increasing of particle volume concentration is beneficial for the back flow of the particles brought by the drilling fluid. This is because particle volume concentration is low, and the interaction or collisions between the particles are also little. The sinking speed of particles is reduced by the resistance between the particles.

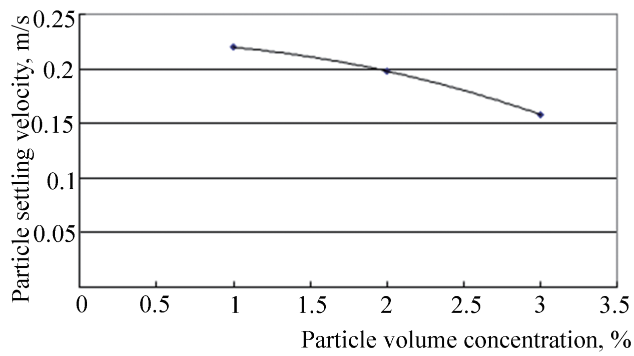

Figure 7
The Curve of Particle Settling Velocity and Particle Volume Concentration

2. EXPERIMENTAL STUDY ON THE PARTICLES MOTION

2.1 Experimental Introduction

Full size annulus experimental apparatus is used in this experiment, as shown in Figure 8. The total height of the experimental annulus aircraft is 13 m. The external pipe is made of steel and pmma (3 m), the diameter of which are Φ114 mm and Φ210 mm respectively. The internal pipe is made of steel, the external diameter of which is Φ114 mm. The entire device is used to simulate the real wellbore annulus.

Steel particles with the diameter of 1 mm, 1.7 mm and 2 mm are used in the experiment. The drilling fluid density is 1.32 g/cm^3, and the drill speed is 90 r/min. Under different particle sizes, fluid displacement and the average annulus velocity, the experiments are conducted.

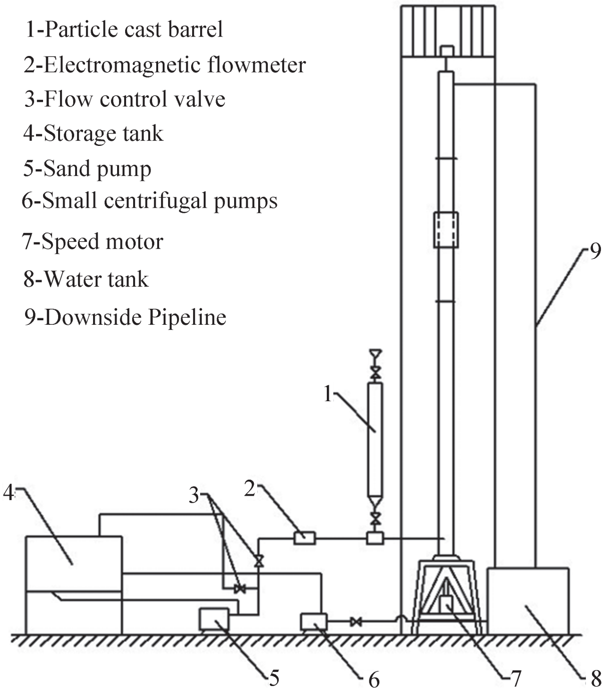

Figure 8
Annulus Experimental Device Sketch

2.2 Experimental Data and Results Analysis

2.2.1 Experimental Statistics

Particle settling velocity v_p in the drilling fluid is calculated as following:

$$v_p = v_f - v_s. \tag{1}$$

Where, v_p - particle settling velocity, m/s; v_f -the average fluid velocity, m/s; v_s-the average particle return velocity, m/s.

Particle lifting efficiency K is defined as the velocity ratio of the average particle return velocity v_s and the average fluid velocity v_f:

$$K = \frac{v_s}{v_f} = \frac{v_f - v_p}{v_f} = 1 - \frac{v_p}{v_f}. \tag{2}$$

Where, K- Particle lifting efficiency, $K \geq 0.5$.

Experimental results are shown in Table 2.

Table 2
Experiment Data Table

Particle diameter mm	Flow L/s	Drilling fluid velocity m/s	Particle volume concentration %	Particle velocity m/s	Particle lifting efficiency	Particle settling velocity m/s	Drill speed r/min
			1	0.85	0.94	0.05	
	22	0.90	2	0.84	0.93	0.06	
			3	0.84	0.94	0.06	
			1	0.96	0.94	0.06	
1	25	1.02	2	0.95	0.93	0.07	
			3	0.96	0.94	0.06	
			1	1.08	0.94	0.07	
	28	1.15	2	1.07	0.93	0.08	
			3	1.06	0.92	0.09	
			1	0.74	0.82	0.16	
	22	0.90	2	0.73	0.81	0.17	
			3	0.75	0.83	0.15	
			1	0.86	0.84	0.16	
1.7	25	1.02	2	0.85	0.83	0.17	90
			3	0.83	0.81	0.19	
			1	0.99	0.86	0.16	
	28	1.15	2	0.97	0.85	0.18	
			3	0.95	0.83	0.20	
			1	0.67	0.74	0.23	
	22	0.90	2	0.67	0.74	0.23	
			3	0.67	0.74	0.23	
			1	0.79	0.77	0.23	
2	25	1.02	2	0.78	0.76	0.24	
			3	0.79	0.77	0.23	
			1	0.90	0.78	0.25	
	28	1.15	2	0.90	0.78	0.25	
			3	0.89	0.77	0.26	

2.2.2 Analysis of Experimental Results

2.2.2.1 The Drilling Fluid Return Velocity Effect on the Movement of Particles

In Figures 9 and 10, with the increasing of the fluid velocity, the particle velocity also increases. The two variables show approximate linear relationship. The settling velocity of particles in drilling fluid increases as fluid velocity climbs, but the impact is very small.

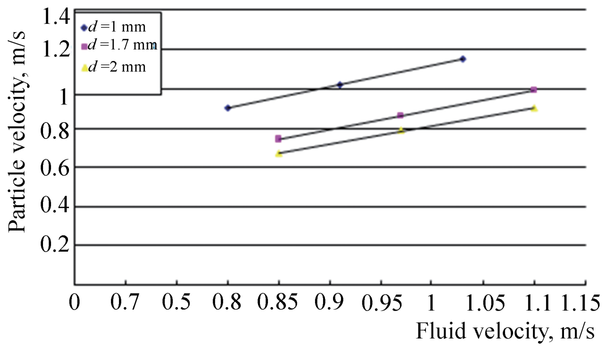

Figure 9
Relationship Between Particle Velocity and Fluid Velocity (φ = 1%)

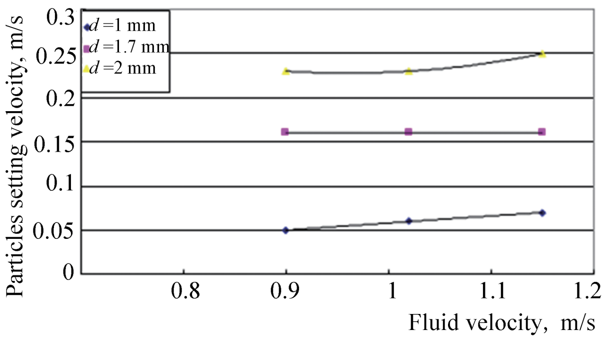

Figure 10
Relationship Between Particles Setting Velocity and Fluid Velocity (φ = 1%)

Particle settling velocity change is due to the drilling fluid with shear thinning. With the large flow rate and shear rate increased, fluid effective viscosity in the annulus decreases. It is not good for the carrying of the particles.

2.2.2.2 Particle Diameter Effect on the Particle Settling Velocity

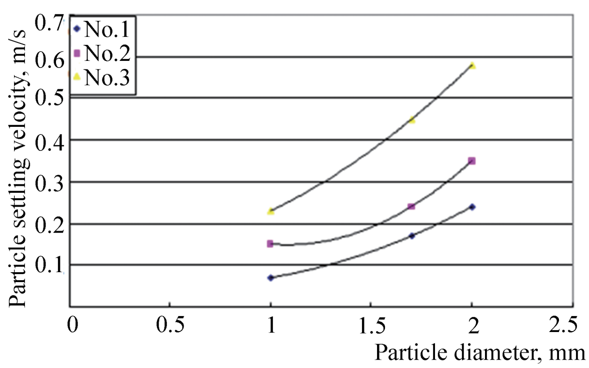

Figure 11
Relationship Between Particle Settling Velocity and Particle Diameter (Q = 25 L/s, φ = 2%)

In Figure 11, for fixed annulus velocity of drilling fluid, the settling velocity of particles in drilling fluid increases with the increasing of the particle diameter. This is because the gravity increases and the flow patterns around change.

2.2.2.3 Particle Volume Concentration Effect on the Particle Settling Velocity

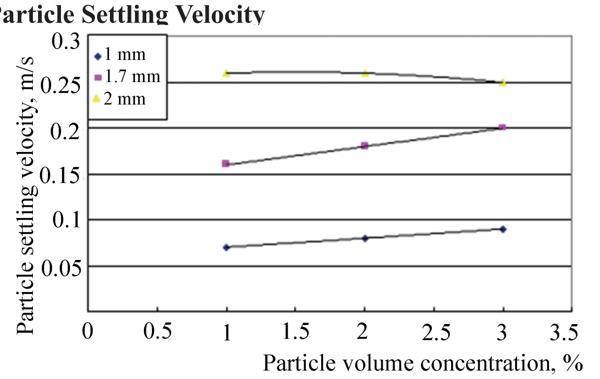

Figure 12
Relationship Between Particle Settling Velocity and Volume Concentration (Q = 28 L/s)

In Figure 12, the particle settling velocity of the 2 mm diameter decreases with the particle volume concentration increases. However, it is exactly the opposite of the 1mm and 1.7 mm. It is mainly because the number of the particles of 2 mm is less than the 1mm or 1.7mm, when the volume concentration is the same.

2.2.2.4 Drilling Fluid Effective Viscosity Effect on the Particle Settling Velocity

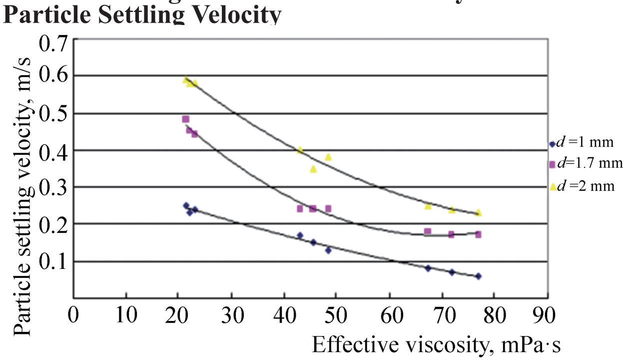

Figure 13
Relationship Between Particle Settling Velocity and Effective Viscosity (Q = 28 L/s, φ = 2%)

In Figure 13, particle settling velocity decreases with the increasing of the fluid effective viscosity. The lifting efficiency of the particle also rises. This is because the increasing of the effective viscosity makes the shear stress generated on the particle increase.

3. DRILLING FLUID PARAMETER OPTIMIZATION

3.1 Consider Particle Lifting-Efficiency Effect on the Annulus Apparent-Density

Since the annulus fluid velocity in the cross section is not the same, generally the velocity in the middle part of the drilling fluid is higher, carrying the particles back. And the velocity on both sides close to the drill pipe and the borehole fluid flow area is lower, making it difficult for the particles to be carried back. Therefore, the particle settling velocity v_p multiplied by the correction factor K' (Generally, $K' = 0.8$), the particle volume concentration in the annulus C_2 is calculated as follows:

$$C_2 = \frac{\frac{v_f}{0.8v_p}\times C_1}{\frac{v_f}{0.8v_p}-1+C_1} = \frac{\frac{1.25}{1-K}\times C_1}{\frac{1.25}{1-K}-1+C_1}. \tag{3}$$

Where, C_1 - Particle volume concentration in the drill, %; C_2 - Particle volume concentration in the annulus, %.

Take different values of C_1 and K, and calculate the values of C_2 and the annulus apparent-density increment.

Table 3
Calculated Data Table

C_1 %	K	C_2 %	The annulus apparent-density increment, g/cm^3
1	0.5	1.66	0.13
	0.7	1.31	0.10
2	0.5	3.29	0.26
	0.7	2.61	0.20
3	0.5	4.9	0.38
	0.7	3.9	0.30

From the above calculation results, with the particle volume concentration increased, the annulus apparent-density increments increases. Take $K = 0.5$, $C_1 = 2\%$ and $C_1 = 3\%$, the annulus apparent-density increments are too large, which may fracture the formation and cause accidents. Take $K = 0.7$, $C_1 = 1\%$, the annulus apparent-density increments are acceptable.

Considering particle lifting-efficiency effect on the annulus apparent-density, the optimal values of drilling fluid parameters are $K \geq 0.7$, $C_1 = 1\%$. Such performance can ensure the efficiency of the particles carried out of the borehole.

3.2 Consider the Particle Suspension in the Static Drilling Fluid

The power law fluid yield stress is zero, and the fluid is deformed as long as the effect of a small force on the fluid. Particle density is greater than that of the fluid. In addition there is a vertical downward force formed by particle gravity and buoyancy force of the particle fluid. Therefore, particles settle. When the particle diameter is small to a certain extent, it will not overcome the yield stress and get a suspension in the fluid. Then sedimentation does not occur, which is known as natural suspended state. When the fluid stops circulating, it can make the solid phase suspension in the annulus to prevent the deposition of the solid phase at the bottom of the borehole. In this case, accidents can be avoided. Conditions for particles sedimentation are shown as follows:

$$\frac{\rho_s}{\rho} \geq 14.25\frac{\tau_0}{gd\rho}+1. \tag{4}$$

Where, ρ_s - the particle density, kg/m^3; ρ - the fluid density, kg/m^3; τ_0 - the yield stress, Pa; d - the particle diameter, m.

When the ρ_s = 7,800 kg/m^3, ρ = 1,320 kg/m^3, conditions for particles sedimentation are calculated: d = 1 mm, τ_0 = 4.5 Pa; d = 1.7 mm, τ_0=7.6 Pa; d = 2 mm, τ_0 = 8.9 Pa.

Therefore, if the fluid performance can be selected in an optimal value $\tau_0 \geq 4$ Pa, the diameter of 1 mm, 1.7 mm and 2 mm particle suspension requirements can be realized.

CONCLUSION

Through the experimental and numerical analysis of solid-liquid two-phase flow pattern in PID, the following conclusions can be drawn:

Particles are unevenly distributed in the annulus. The settling velocity of particles in drilling fluid is influenced by the density unevenness. However, particle settling velocity decreases with the increasing of effective fluid viscosity.

As the fluid density and average velocity increases, the particle velocity climbs in the annulus. Therefore, particles are easier to be carried out of the borehole by the drilling fluid.

Considering the particle lifting-efficiency K has a major influence on the annulus apparent-density, and the optimal values of drilling fluid parameters are $K \geq 0.7$, $C_1 = 1\%$, $\tau_0 \geq 4$ Pa. Such performance can ensure the efficiency of the particles to be carried out of the borehole.

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