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Paper

Numerical Simulation of Micro-annulus Carrying Capacity

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ABSTRACT

With the development of oil and gas exploration and extraction to the deep formations, the deep and ultra-deep wells are playing more and more important roles in drilling industries. To improve the drilling performance in the deep formations, we proposed a new method of a Partial-Under-Balance drilling technique modulated by coiled tubing. This paper mainly studied the cuttings-carrying capacity of the micro-annulus between the drill string and the coiled tubing using a numerical simulation method. For a low flow rate from 14 L/s to 18 L/s, a critical velocity was found to remove the drilling cuttings away from the flow nuclei with a rotation speed of 60 rpm. And the position of the flow nuclei doesn't move with the improvement of the rotation rate of the drill pipe (DP) while the rotation speed inside the flow nuclei increases significantly with the flow rate, making a high wellbore hole cleaning efficiency. Through the simulation, the shear speed of the drilling mud is a cubic function of the distance to the center of DP and a liner function of the DP rotation speed. Compared with the DP rotation rate, the results of the orthogonal test demonstrate the flow rate contributes more to the cuttings-carrying capacity of the micro-annulus.

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1. INTRODUCTION

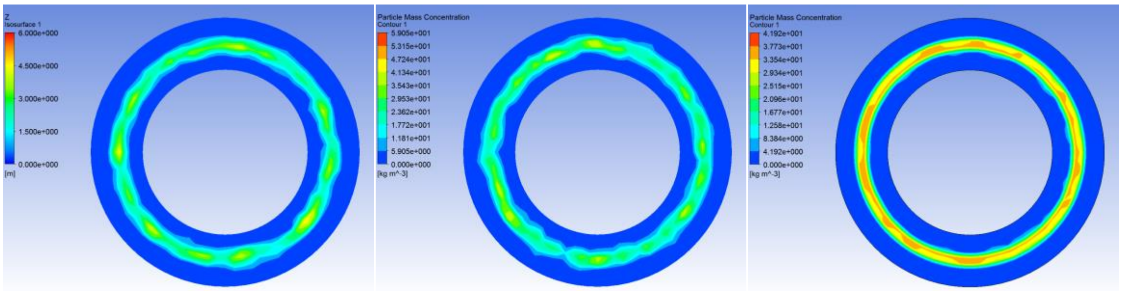
With the development of oil and gas exploration and extraction to the deep formations, the number of deep and ultra-deep wells increased significantly in the past decade. Along with the improvement of the formation depth, the rock is subject to higher pressure, usually leading to a higher rock hard ness and thus a low rate of penetration (ROP) of the bit. ,. To cut down the drilling cycle and the drilling cost, the method of underbalanced drilling is increasingly applied to such hard strata formations. With a wide application in more than 20 countries, the underbalanced drilling method is proved to be 2 to 10 times more efficient than the conventional drilling and can save much stimulation cost in the later production (Li. 2015). However, underbalanced drilling is also limited to its application due to high drilling costs, poor drilling safety, and drilling fluid selection difficulties (Li. 2015; Zhai et al. 2012; Chen. 2000; Luo et al. 1999). To improve the drilling performance, coiled tubing is gradually combined with the underbalanced drilling. S. R. Scherschel and D. G. Graves (S. R. Scherschel, D. G. Graves. 1996) pointed out that the use of coiled tubing for underbalanced drilling should be a good choice for underbalanced drilling. However, due to fact that the coiled tubing cannot rotate, the drill cuttings cannot be removed outside the wellbore efficiently (S. R. Scherschel, D. G. Graves. 1996; Leising L J, I C Walton. 2002). Kelessidis and Bandelis (Kelessidis and Bandelis, 2004) used experimental and theoretical methods to study the critical flow velocity of cuttings in horizontal and inclined wells during, coiled tubing drilling. T. Hemphill, and K. Ravi (T. Hemphill and K. Ravi, 2006) studied the effect of drill pipe rotation on cuttings carrying in eccentric shaft. In order to improve the ROP and reduce the residual cuttings inside the hole, we proposed a new method of a Partial–Under-Balance drilling technique modulated by coiled tubing. The new method separates the annular into two parts using the annular packer, respectively circulating high density drilling fluid in the above part of the wellbore and low density drilling fluid near the bit. The micro annular constructed by coiled tubing and drilling pipe changes the general cuttings-carrying passage and achieves a high hole cleaning efficiency with a low flow rate. During the drilling process, the coiled tubing passes through the center of the drill pipe while the drill pipe rotates and drives the drill bit to break the rock. The drilling fluid flows through the backflow connector into the micro-annulus between the tubes and pipes, then flows out of the wellbore. A number of studies have been applied to the conventional drilling optimization (Leising L J, I C Walton. 2002; Woo N et al, 2011), but few literatures provide useful information to such a micro-annulus cutting-carrying method. This paper mainly focuses on the rotation rate effect and the flow rate effect on the cuttings migration

2. ANALYSIS OF NUMERICAL SIMULATION RESULTS

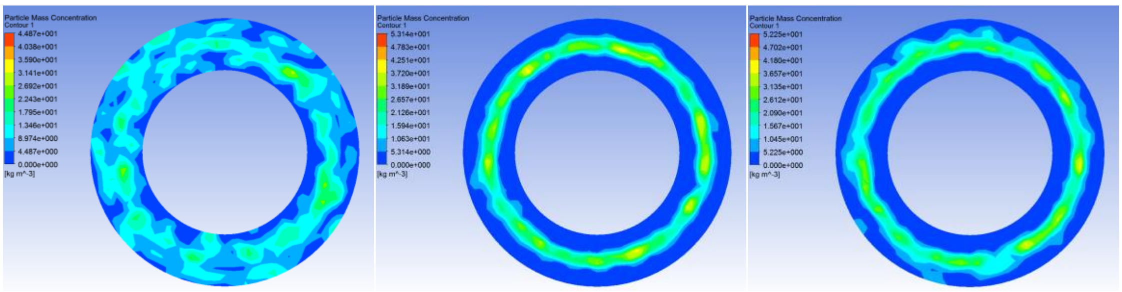
2.1 Influence of Pipes Rotating Speed on Carrying Cuttings in Micro Annulus

In the study of the influence of pipes rotary speed on carrying cuttings in micro annulus, there were simulated pipes rotary speed at 0rpm, 30rpm, 50rpm, 60rpm, 70rpm, 100rpm and 150rpm. In order to eliminate the influence of boundary conditions on cuttings migration, the distribution of cuttings is observed at a distance of 4 m from the inlet position and 2 m from the exit position. Figure 1 shows the distribution of cuttings at different rotational speeds in 18L/s flow rate. From the figure1, the cuttings are more likely to be distributed in the middle of the micro-annulus, which may be related to the velocity distribution of the drilling fluid in micro annulus.

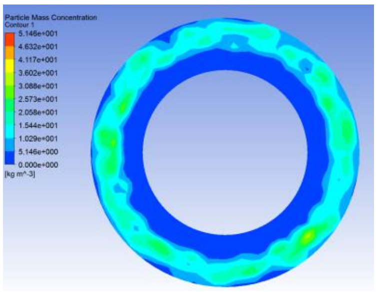
To figure out the DP rotation rate effect on the cuttings migration, a series of rotation rates were set as O rpm, 30 rpm, 50 rpm, 60 rpm, 70 rpm, 100 rpm, and 150 rpm. The interested area is the part 4 m away the inlet port and 2 m away from the outlet port. Firstly, an overall view of the drill cuttings distribution inside the annulus is needed to see whether the rotation speed has an effect on the cuttings migration. Then, further discussion is required to study the rotation rate effect if there is a significant difference among those cuttings distribution. As is shown in Figure.1, the drill cuttings are mainly distributed near the middle part of the micro-annulus under a flow rate of 18 L/s. And Figure.2 proposed a radial velocity distribution at different positions of the drilling fluid inside the micro-annulus under different rotational speeds. Obviously, a flow nuclei is shown near the middle of the micro-annulus and it nearly doesn't get changed with the various rotation rates of the drill pipe. Through the similar distribution of the drill cuttings and the mud velocity inside the micro-annulus, the mud velocity should be designed to remove those cuttings.



（a）18L/s,0rpm （b）18L/s,30rpm （c）18L/s,50rpm



（e）18L/s,70rpm （f）18L/s,100rpm （d）18L/s,60rpm



（g）18L/s,150rpm

Figure 1. The Distribution of Drill Cuttings under Different Rotational Speeds to a 18L/s Flow Rate.

Figure 2 is the curve of drilling fluid velocity distribution under different rotational speeds to a 18L/s Flow Rate.

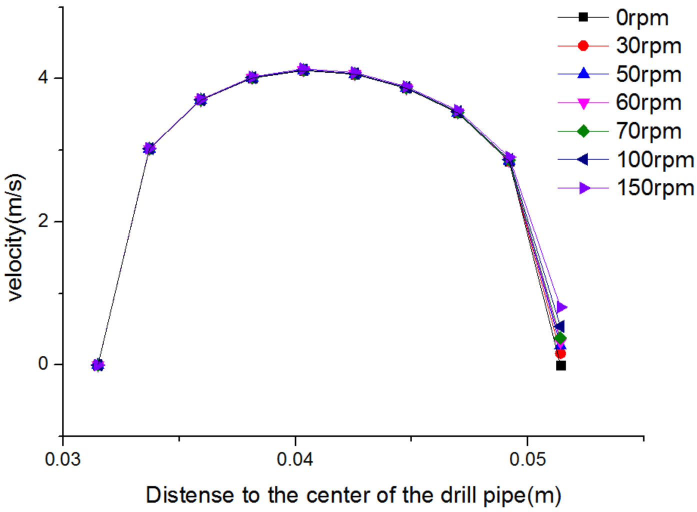


Figure 2. Drilling Fluid Velocity Distribution under Different Rotational Speeds to a 18L/s Flow Rate

However, with the increase of the rotating speed of the drill pipe, it can be seen from the distribution of the cuttings concentration that the cuttings tend to migrate to the outside. When the rotational speed is lower than 50rpm, the cuttings are mainly distributed in the middle of the micro annulus, as shown in (a), (b) and (c) in Fig1. But when the drill pipe speed increases to 60rpm, as shown in Figure 1 (d), cuttings are distributed throughout the micro-annulus. Though the middle area still has a maximum cuttings concentration, the drill cuttings are more evenly distributed inside the micro-annulus under a rotation rate of 60 rpm. Then as the rotation rate keeps increasing gradually, the drill cuttings re-gathered near the middle of the micro-annulus. In more details, the high concentration of the drill cuttings tends to move radially outward under a high rotation rate. Especially, if we take a close look to the cuttings distribution under 150 rpm rotation rate, the high rotation speed of the drill pipe results to a much high cuttings concentration near the drill pipe but a quite low concentration near the coiled tubing. In view of the movement of the cuttings distribution in the micro-annulus, few data support the mud velocity changes significantly with the rotation speeds. Therefore, the flow nuclei doesn't have a predominant effect on the cuttings distribution.

The tangential velocity of the drilling fluid in the micro-annulus is plotted as shown in Fig 3. The tangential velocity of the drilling fluid increases with the distance to the center of the drill pipe. The tangential velocity of the drilling fluid in the micro-annulus under a high rotation rate is higher than that of the drilling fluid at the same position at low rotational speed and requires larger centripetal force according to the centripetal force formula, similar to Sun et al's studies (Sun et al. 2014).

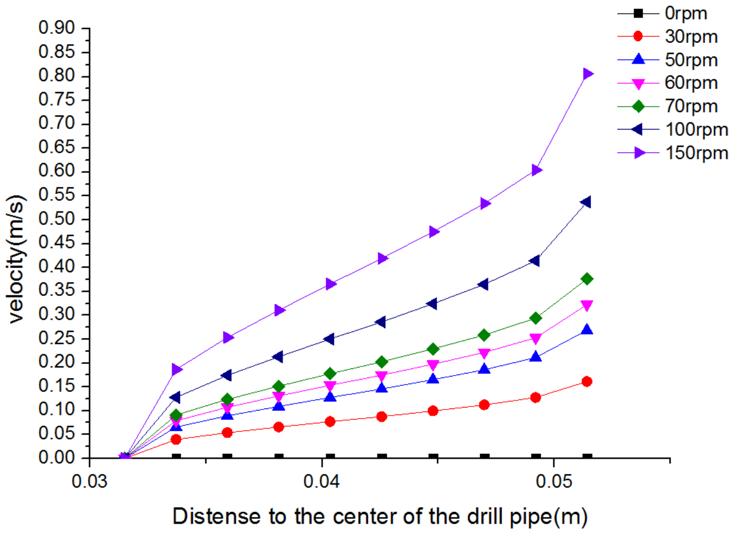


Figure 3. Drilling Fluid Tangential Velocity Distribution under Different Rotational Speeds to a 18L/s Flow Rate

$$F = \frac{m v_T^2}{r} \tag{1}$$

In the drilling process, it's the drilling fluid viscosity force that provides centripetal force for the cuttings. Therefore, with the same drilling fluid parameters and cutting parameters, the high drill pipe rotating speed requires drilling fluid to provide a higher viscous force for the cuttings as a centripetal force. However, the viscosity of the drilling fluid is relatively stable over a certain drilling section. If the viscous force of the drilling fluid does not provide sufficient centripetal force for the cuttings, the cuttings at this position will produce centrifugal motion and move radially outward. Thus as the drill pipe rotating rate increases, the cuttings concentration distribution moves radially outward.

Figure 4 presents the cuttings concentration along the radial distance to the DP center under various rotation rates. It indicates not only a function of the cuttings concentration to the rotation rates but a function between the cuttings distribution along the radial distance. Moreover, the peak cuttings concentration also tends to move to outside, near the inside wall of the drill pipe, along with the increasing of the rotation rates.

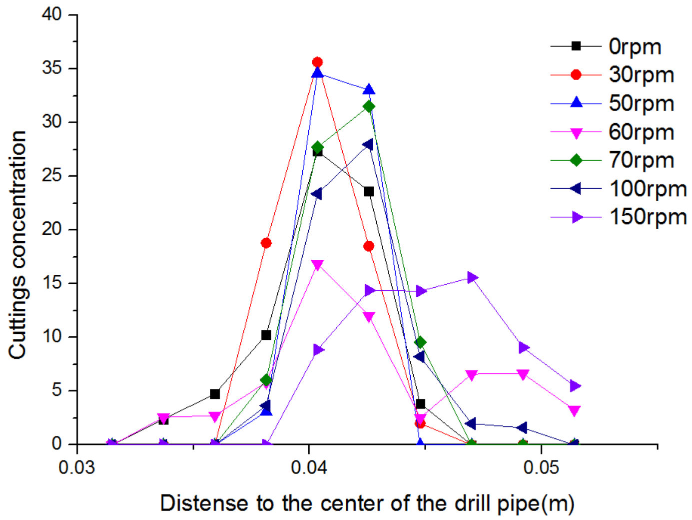


Figure 4. Cuttings Concentration Distribution under Different Rotational Speeds to a 18L/s Flow Rate

In order to find the relationship between the tangential velocity and the rotational speed in the micro-annulus, a plot of the tangential velocity at different points and the rotating speed of the drill pipe versus the distance was drawn as Fig 5. Obviously, the relation between the tangential velocity and the rotating speed of each point can be approximated as a linear function. Define a linear equation as V=ay+b, where V is the tangential velocity and y is the rotation rate. a and b are two parameters related to the position of each position. Then, the values a and b can be obtained and summarized in Table.1.

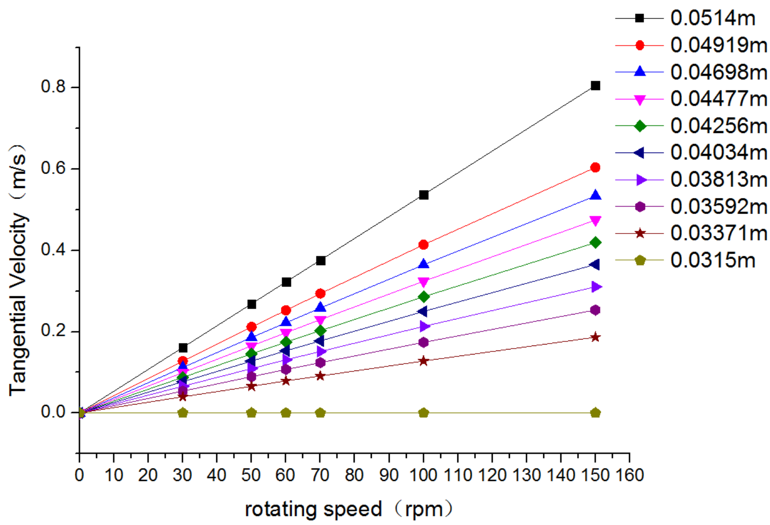


Figure 5. The Tangential Velocity Curve for Each Point under Different Rotating Speeds

Table 1. Parameters a and b at different points

Distance to the center of the drill pipe(m)	Parameter a	Parameter b
0.0514	0.0054	0.0000007
0.04919	0.004	0.0074
0.04698	0.0036	0.0058
0.04477	0.0032	0.005
0.04256	0.0028	0.0044
0.04034	0.0024	0.0044
0.03813	0.0021	0.0043
0.03371	0.0012	0.0027

Plot a and b versus the distance x to the center of the drill pipe, and eliminate the outlier b near the inside wall of the drill pipe. To further increase the fitting accuracy, we use cubic functions to fit the a and b to the distance. Then the a and b values at different positions can be calculated as the following equations. :

$$a = 1281.5x^3 - 157.32x^2 + 6.5598x - 0.0903 \tag{2}$$

$$b = 4163.5x^3 - 507.55x^2 + 20.671x - 0.2768 \tag{3}$$

The relationship between the tangential velocity and the drill pipe rotation rate and the position of each point is finally obtained by substituting the a and b parameters into the linear function of the tangential velocity and the DP rotation rate.

$$v_T = \left(1281.5x^3 - 157.32x^2 + 6.5598x - 0.0903\right)y + 4163.5x^3 - 507.55x^2 + 20.671x - 0.2768 \tag{4}$$

Where x is the distance from the point to the center of the drill pipe, and y is the rotating speed of the drill pipe.

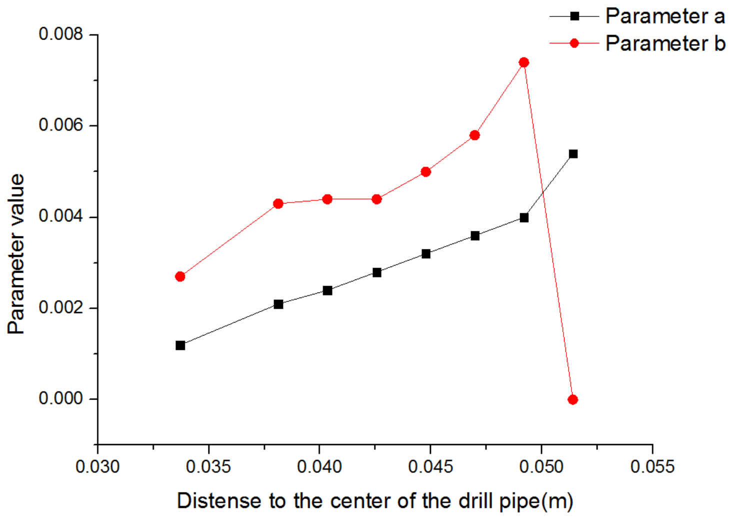


Figure 6. Parameter Curves of Different Points

The residual mass of the debris in the micro annulus is count up and plotted as shown in Fig 7.

It indicates a minimum value of residual cuttings mass in the micro-annulus when the rotation speed is 50 rpm to a 18L / s flow rate. In addition, the residual cuttings mass tends to decrease first but then increase with the rotation rates. Meanwhile, there should be an optimal rotation rate around the valley (50 rpm herein). Given Fig. 2 and Fig. 4, when the drill pipe rotating speed is at 50 rpm, the peak value of the cuttings concentration at the corresponding points is 0.04 m to 0.045 m from the center of the drill pipe. This is where the flow nuclei of the drill fluid in the micro-annulus. Since the high speed makes the cuttings deviate from the nuclei of the drilling fluid in the micro-annulus, thus explaining why there is an optimal rotational speed for carrying the cuttings.

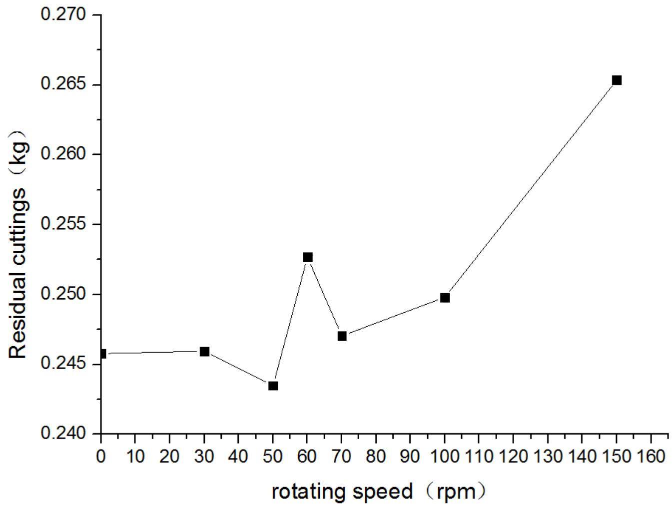
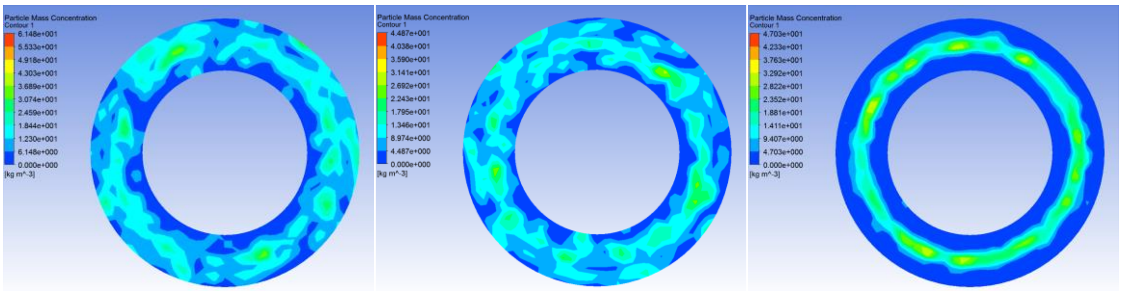


Figure 7. Residual Cuttings in Micro-Annulus under 18L / s Flow Rate

2.2 Influence of Flow Rate on Carrying Cuttings in Micro Annulus

Before the investigation of the flow rate effect on the cuttings migration, set the DP rotation rate as 60 rpm as a baseline firstly. Figure 8 shows the distribution of the drill cuttings under different drilling fluid flow rates. As is shown in the illustrations, when the inlet speed was 2.7m / s and 3.5m / s, the drill pipe rotating speed 60rpm is some kind of critical rotation rate since the drill cuttings are distributed evenly throughout the micro-annulus. However, when it comes to the third flow rate of 22L/s (4.2 m/s in velocity), 60 rpm is no longer a critical speed because the cuttings are mainly focused near the middle of the micro-annulus.



（a）14L/s(2.7m/s),60rpm （b）18L/s(3.5m/s),60rpm （c）22L/s(4.2m/s),60rpm

Figure 8.Cuttings Distributions under Various Flow Rates to a 60 rpm Rotation Rate

To get a better understanding the flow rate effect on the cuttings distribution, three cures are created in Figure.9 along with the distances. t can be seen from the curve that when the drilling fluid flow rate is 14L / s and 18L / s (corresponding to the inlet velocity of 2.7m / s and 3.5m / s), the distributions of cuttings are evenly since the overall distribution fluctuates with the radial positions, which is supported by illustrations (a) and (b) in Figure.8. .When the drilling fluid flow rate is 14L / s and 18L / s, the critical speed of the drill pipe is 60rpm. On the contrary, the curve to 22L/s flow rate is quite smooth with a large amount of drill cuttings concentrated in the middle area of the micro-annulus (shown in illustration (c) in Figure.8.

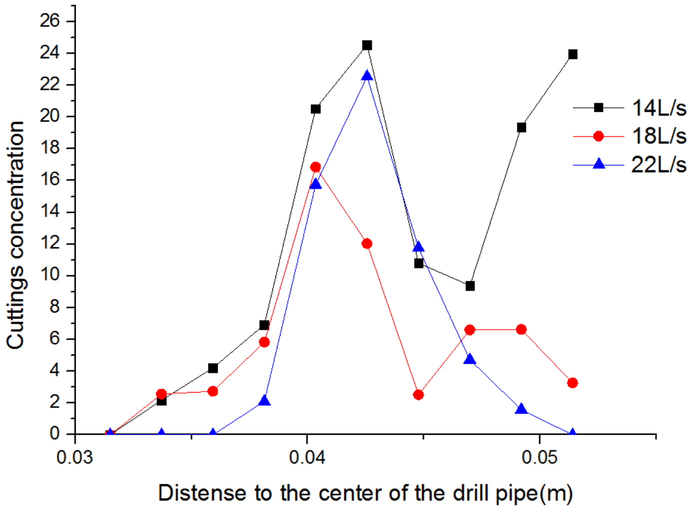


Figure 9. Cuttings Distribution Curve at Rotating Speed of 60rpm

Obviously, the flow rate significantly influences the residual cuttings distribution. Thus, another plot is carried out to analyze the residual cuttings mass changes with the flow rates under two quite distinguished rotation rates, 60 rpm and 150 rpm respectively (Figure.10). Firstly, the residual cuttings in the micro-annulus are reduced as the drilling fluid flow rate increases for both these two rotation rates. However, the absolute value of the slope of the residual cuttings mass curve from low to medium flow rate is significantly greater than the slope of the residual cuttings mass curve in the micro annulus from medium to high rotating speed. It is speculated that with the increase of the cleaning efficiency of drilling fluid on cuttings does not reacts linearly with the improvement of the drilling mud flow rate. When the drilling fluid flow rate increased to a certain value, the residual cuttings won’t continue decreasing.

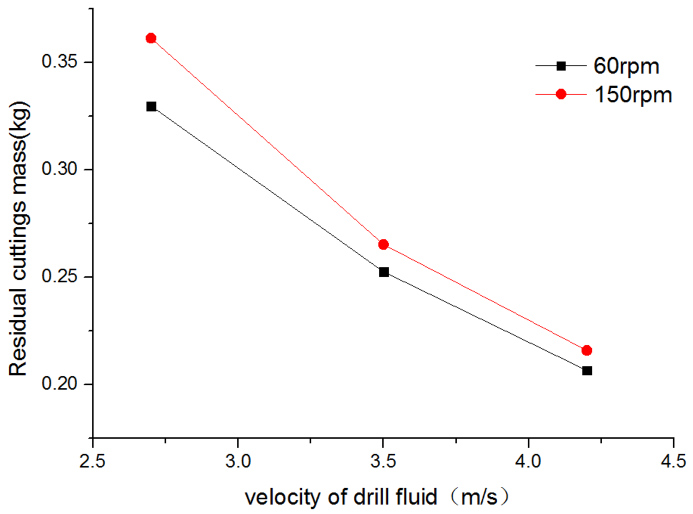
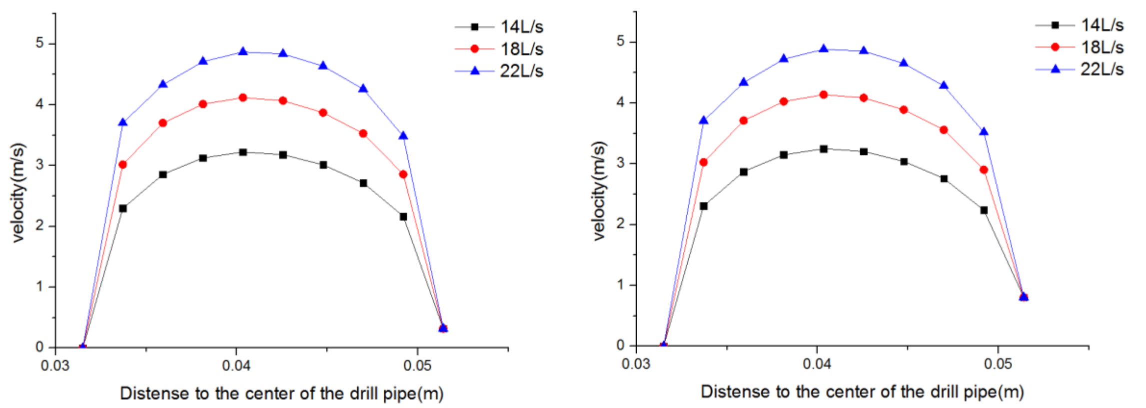


Figure 10. Residual Cuttings at 60 rpm and 150 rpm under Different Flow Rate

Figure 11 shows the fluid velocity distribution of the drilling fluid under 60 rpm and 150 rpm. As we can see from the graph, at a speed of 60 rpm and 150 rpm, the velocity of the drill fluid increases with the increase of flow rate. And the increase in the flow rate of the drilling fluid does not change the fluid nuclei position in the micro-annulus. Therefore, the drilling fluid tends to have a higher cuttings-carrying capacity with the improvement of the flow rate in micro annulus. Similarly, the improvement of the fluid velocity also tends to get smaller from 18L/s to 24 L/s, thus lowering the absolute improvement of hole cleaning efficiency when compared with the improvement from 14 L/s to 22 L/s.



（a）60rpm velocity under different flow rate （b）150rpm velocity under different flow rate

Figure 11. Velocity Distributions at 60 rpm and 150 rpm for Different Flow Rate

The mass of the residual cuttings in the micro annulus under different flow rate and rotating speed is plotted as a curve， such as figure 12. It indicates an optimal rotation rate to efficiently remove the drill cuttings for a low flow rate 14 L/s. Compared with the low flow rate 14 L/s, the residual cuttings mass is relatively smooth under a medium flow rate of 18 L/s but still have an optimal rotation speed for the cuttings migration. However, as for the high flow rate 22 L/s (4.2 m/s in velocity), the residual cuttings mass keeps increasing with the rotation rates, which means the rotation rate doesn't help with hole cleaning and even can make it worse.

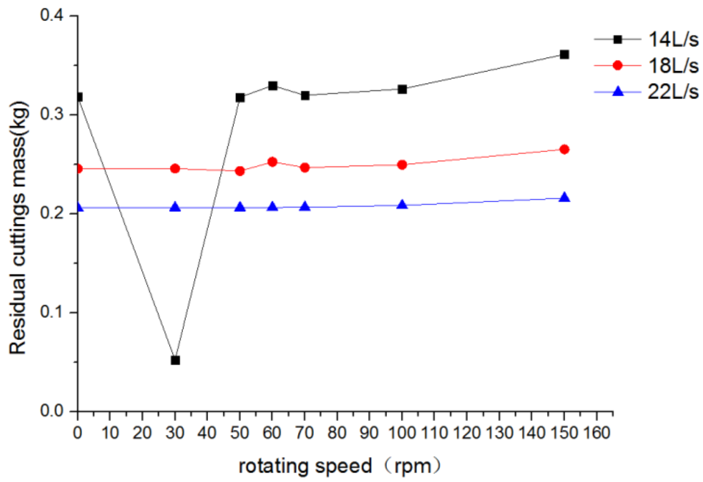


Figure 12. Residual Cuttings of the Different Flow Rate at Different Rotating Speed

To further investigate the rotation rate effect on the cuttings radial distribution under a high flow rate conditions, Figure.13 is carried out with a 22 L/s flow rate. As shown in the figure, the cuttings in the micro annulus are mainly distributed in the center of the drill pipe from 0.03592m-0.04477m, which is the flow nuclei area of the drilling fluid. However, with the increase of the rotating speed, we find that the cuttings in the middle of the micro annulus are lower, and it is found that the concentration of cuttings near the inner wall of the drill pipe increases.

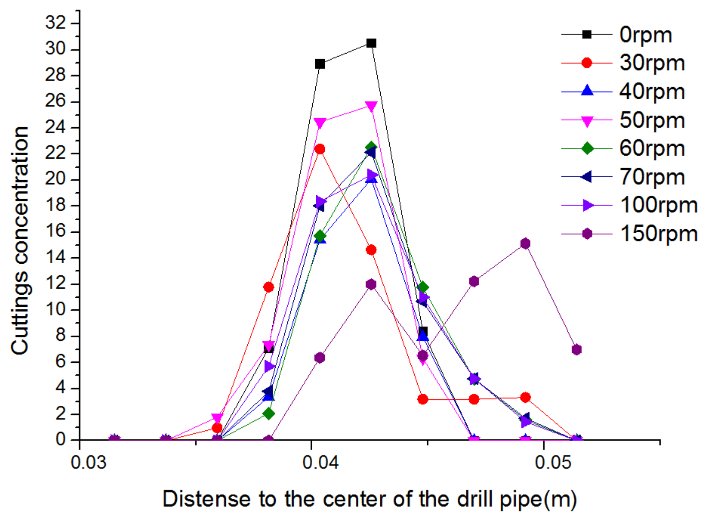
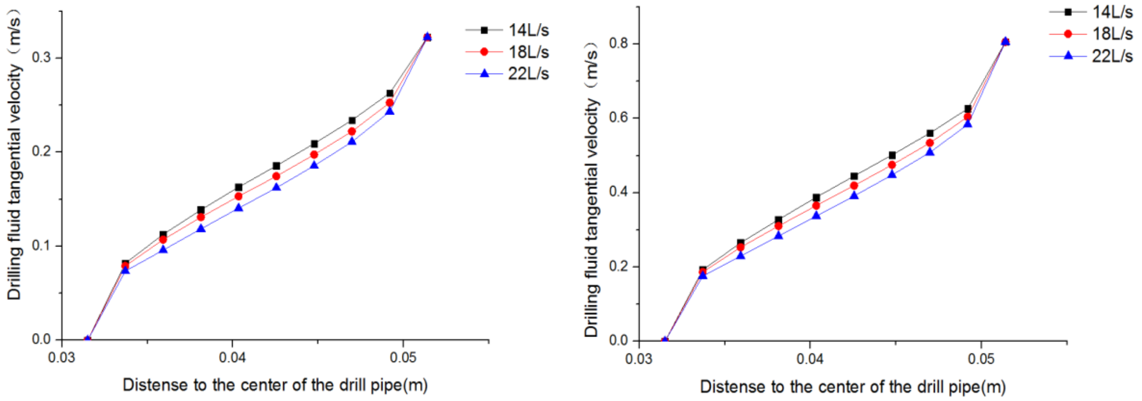


Figure 13. Distribution of Cuttings at 22L/s Flow Rate

In addition, we plot the tangential velocity distribution of the drilling fluid under each flow rate as Fingure.14. Obviously, the flow rate mainly affects the tangential velocity distribution around the flow nuclei but less works near the inside wall of the drill string and the outside wall of the coiled tubing. For the flow nuclei area, the tangential velocity of the drilling fluid decreases with the increase of the flow rate. In the case of 22 L/s flow rate, the tangential velocity of the drilling fluid at the same location is the smallest. Therefore, under the high flow rate, the rotational speed has little effect on the cuttings concentration distribution. Because the tangential velocity at the same position is small at the corresponding high flow rate, the viscous force of the drilling fluid can provide the centripetal force, and the influence on the distribution of the cuttings in the micro-annulus is negligible.



（a）The tangential velocity of drilling fluid at 60 rpm

（b）The tangential velocity of drilling fluid at 150 rpm

Figure 14. The Tangential Velocity of Drilling Fluid at 60 rpm and 150rpm

3. ORTHOGONAL TEST

In order to analyze the influence weight of the flow rate effect of the drilling fluid and the rotating speed effect of the drill pipe on the micro annulus carrying capacity, this numerical simulation designed a Orthogonal test as Table.2. The data were processed and correlated by professional software. Finally, the flow rate effect is proved to be much more efficient to improve the micro-annulus cuttings-carrying capacity than the rotation rate effect.

Table 2. Orthogonal experimental tables

Flow rate of drill fluid (L/s)	Rotating speed of drill pipe (rpm)	Mass of residual cuttings in micro – annulus (Kg)
14	150	0. 36129
22	100	0. 208685
22	30	0. 206356
14	70	0. 31995
22	60	0. 20672
14	60	0. 329817
18	50	0. 243492
18	30	0. 245959
22	70	0. 206809
14	50	0. 318083
22	150	0. 216052
18	100	0. 249815
14	0	0. 31842

18	0	0.24578
14	100	0.326387
18	70	0.247046
18	150	0.265353
22	50	0.206535
14	30	0.052717
18	60	0.252686
22	0	0.206183

Table 3. Analysis of variance in orthogonal test

Source of variance	Mean squared difference	F value	Significance
Flow rate of drill fluid	0.012	3.2	High
Rotating speed of drill pipes	0.004	1.1	low

4. CONCLUSION

To improve the drilling performance in the deep hard formations, this paper proposed and verified a new drilling method as Partial-Under-Balance drilling technique modulated by coiled tubing. This method can achieve a high drilling performance with a low flow rate through a micro-annulus created by coiled tubing and drilling string. This paper mainly focuses on the numerical simulations analysis on the micro-annulus cuttings-carrying capacity and draws out the following conclusions, which may provide some guidance on other similar researches. .

（1）At medium and low flow rate (14L/s and 18L/s), there is a critical rotation rate that allows the cuttings to move outward from the flow nuclei, which is 60rpm.

（2）With the increase of rotating speed, the micro-annulus flow nuclei does not move. With the increase of rotating speed, the tangential velocity of drilling fluid in micro annulus increases. And in the 18L / s flow rate, the cuttings in the micro annulus are moved to the outside. The tangential velocity of the drilling fluid in the micro-annulus is defined as a cubic function of the distance to the center of the drill pipe and a linear function of drill pipe rotating speed.

（3）With the increase of drilling fluid flow rate, the velocity of flow nuclei increases, and the mass of residual cuttings in micro annulus decreases. Therefore, the increase of drilling fluid flow rate will help the micro-annulus to carry cuttings, but when the drilling fluid flow rate increased to a certain extent, the effect on improving cuttings-carrying capacity is not significant.

（4）According to the results of orthogonal test, the flow rate plays a much more important role in enhancing the micro-annulus cuttings-carrying capacity than the rotation rate effect.

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NOMENCLATURE

F Centripetal force, N
m Mass, kg
v_T Tangential velocity, m/s
r Rotation radius, m
a Intermediate parameter
b Intermediate parameter
x Distance to the center of the drill pipe, m
y Rotating speed, rpm