Key Structural Parameters Analysis of Effective HydroClean Drill Pipe

Chen Tao\textsuperscript{1,2,a} Jin Yugo\textsuperscript{3,b} Chen Feng\textsuperscript{3,c} Di Qinfeng\textsuperscript{4,d} Wang Wenchang\textsuperscript{4,e} Li Qing\textsuperscript{1,1f}

\textsuperscript{1}School of Computer Engineering and Science, Shanghai University, Shanghai 200072, China
\textsuperscript{2}Admissions and Career Services Office, Shanghai University, Shanghai 200072, China
\textsuperscript{3}School of Mechatronics Engineering and Automation, Shanghai University, Shanghai 200072, China
\textsuperscript{4}Shanghai Institute of Applied Mathematics and Mechanics, Shanghai University, Shanghai 200072, China
\textsuperscript{a}chentao0709@shu.edu.cn, \textsuperscript{b}2603765066@qq.com, \textsuperscript{c}chenfeng536@126.com, \textsuperscript{d}qinfengd@sina.com, \textsuperscript{e}wangwenchang1982@163.com, \textsuperscript{f}qli@shu.edu.cn

Abstract. In directional well, horizontal well and extended reach well, there is a common problem that cuttings bed is easy to form in the process of drilling in highly deviated section. To solve this problem, an Effective Hydro Clean Drill Pipe (EHCDP) is designed, and the flow characteristics of the annular flow field under the action of EHCDP are analyzed by using computational fluid dynamics (CFD) simulation technology. On this basis, the key structural parameters affecting the swirl characteristics of EHCDP are studied. The results show that when the number of spiral grooves is 3, the axial and tangential velocities of annular fluid in spiral groove section will be greater, which is conducive to carrying and removing cuttings. Compared with the inclination angle of spiral groove with 1000 mm lead, that of spiral groove with 500 mm lead is larger, which has more obvious stirring effect on flow field, and the effect of cuttings removal is better. In addition, the spiral groove with 90 degree groove angle is more conducive to cuttings removal than the spiral groove with 30 degree groove angle. The results can provide a basis for the selection and optimization of structural parameters of spiral groove.

1. Introduction
The increasingly harsh drilling conditions and progressive drilling technology make directional drilling technology more and more widely used. Directional wells (especially directional wells with high deviation and large extended reach) in various oilfields account for an increasing proportion of their drilling. With the deepening of exploration and development, directional drilling technology has developed rapidly. At the same time, the horizontal section of horizontal wells should be extended longer, drilling speed faster and wellbore smoother, so as to develop oil and gas resources economically and efficiently \cite{1-2}. Horizontal well drilling technology was born in Europe in the 1980s, and quickly swept across the oil drilling and production industry \cite{3}. According to statistics, more than 50,000 horizontal wells have been drilled in more than 60 countries and regions such as the...
United States, Canada and Russia in 2014, of which 88.4% are in the United States and Canada [4]. In China, horizontal well technology has been applied to varying degrees in Daqing Oilfield, Tarim Oilfield, Jidong Oilfield and Liaohe Oilfield [5]. The development of horizontal well technology has solved many technical problems for drilling industry. However, both practical and experimental studies show that because of the large deviation and horizontal displacement of such directional wells, it is difficult to carry cuttings, so cuttings are easy to accumulate and form cuttings beds during drilling.

In the drilling process, the deposition of cuttings and the formation of cuttings bed may lead to a variety of complex downhole problems. It mainly includes: 1) Testing tools and logging tools are easily blocked, causing difficulties in testing and measuring. 2) It will cause difficulties in casing and cementing operations and poor cementing, which can easily lead to oil, gas and water interflow. 3) The existence of cuttings bed may lead to the phenomenon of high friction, high torque and drag pressure of drill pipe, and even serious downhole accidents such as sticking and breaking of drilling tools [6-9]. This will affect the safety of drilling operations and drilling efficiency.

The author once investigated the cuttings bed removal technology at home and abroad, and analyzed the working mechanism of EHCDP by using CFD technology [10]. On this basis, this paper will further study the influence of key structural parameters of EHCDP spiral groove on the removal effect of cuttings bed, so as to provide basis for the selection and optimization of structural parameters.

2. Hydrodynamic model of EHCDP

The key feature of EHCDP is that the spiral groove structure is arranged, as shown in Figure 1a, and the profile of spiral groove is shown in Figure 1b. The basic structural parameters used in this paper are as follows: the outer diameter of drill pipe is 127 mm, the maximum outer diameter of spiral groove section is 165.1 mm, the borehole diameter is 215.9 mm and the corresponding eccentricity is 15 mm [10].

In practice, EHCDP will rotate at a certain speed (usually 60 r/min), which will cause the solid boundary to change with time. Therefore, the fluid flow in annulus must be calculated by unsteady flow. For this kind of unsteady flow problem, it is difficult to use integrated grid to calculate. Therefore, the fluid near the surface of drill pipe is divided into different computational domains by sliding mesh technology, so that the flow field control equation can be solved in each subdomain. At the interface of sub-domains, the flow field information of each sub-domain is exchanged by converting the velocity into absolute velocity. In addition, the whole fluid region is divided into hexahedral meshes, the meshes at the inner wall are shown in Figure 2a, and the meshes at the channel section are shown in Figure 2b [10]. Among them, the purple region and the green region represent different computational domains.
In this paper, the realizable k-ε turbulence model is selected for the governing equation of hydrodynamics. The transport equations of turbulent kinetic energy k and turbulent dissipation rate are as follows [11, 12]:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu + \mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon \quad (1)
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu + \mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_{\mu} \varepsilon \frac{\varepsilon}{k + \sqrt{\varepsilon \mu}} \quad (2)
\]

In addition, the inlet of the model is calculated with a velocity boundary of 1.5 m/s (that is, the flow rate of the fluid is 36 L/s). The outlet adopts pressure boundary with the size of 30 MPa. The borehole wall is fixed. And the outer surface of the drill pipe is a rotating wall with a rotating speed of 60 r/min [10].

3. Analysis of the effect of key structural parameters of EHCDP on the flow characteristics of annular flow field

First of all, it should be noted that: Lower static pressure in the middle of spiral groove area, higher dynamic pressure in small annulus, greater axial and tangential velocities will be more conducive to carrying cuttings and clearing cuttings bed. The swirl structure generated by spiral groove can also improve the removal effect of cuttings.

3.1. Analysis of the influence of channel number on annular flow field

Figure 3 shows the hydrostatic pressure distribution in annulus under different number of helical groove structures. It can be seen from the graph that they have similar static pressure distributions for annular fluids. The high pressure zone is formed near the inlet side of each groove, and the low pressure zone is formed near the hook angle of each spiral groove. However, with the increase of the number of grooves, the hydrostatic pressure of annular fluid in spiral groove section increases gradually. This makes it more difficult for the cuttings to enter the hook angle area, which is not conducive to the removal of cuttings.

![Figure 3](image)

Figure 3. Distribution of hydrostatic pressure in annulus.

Figure 4 shows the hydrodynamic pressure distribution in annulus under different number of helical groove structures. From the graph, it can be seen that the dynamic pressure distribution law is similar. They all have high dynamic pressure in small annulus. At the same time, with the increase of the number of spiral grooves, the dynamic pressure of annular fluid in spiral groove section decreases gradually, including small annulus. This is because with the increase of the number of spiral grooves, the annulus space will gradually increase, resulting in a gradual decrease of dynamic pressure. However, the decrease of dynamic pressure in small annulus is not conducive to the erosion of bottom hole cuttings.
Figure 4. Distribution of hydrodynamic pressure in annulus.

Figure 5 shows the tangential velocity vector of annular fluid under the action of different number of spiral groove structures. From the graph, it can be seen that the annular fluid has a higher positive tangential velocity in the small annulus under the action of various spiral groove structures, and a higher reverse tangential velocity in the center of each spiral groove. At the same time, according to the direction of velocity vectors in the graph, they all produce vortices which are beneficial to cuttings removal. This also shows the influence of spiral channel structure on annular flow field and the feasibility of using spiral channel structure to help remove cuttings bed. However, as the number of spiral grooves increases, the tangential velocity of annular fluid in spiral groove section decreases gradually.

Figure 5. Tangential velocity vector diagram of annular fluid.

Figure 6 shows the axial velocity distribution of annular fluid under different number of helical groove structures. As can be seen from the graph, they all have higher axial velocity in the small annulus. Accordingly, with the increase of the number of spiral grooves, the axial velocity of annular fluid in spiral groove section decreases. The small axial velocity will not be conducive to carrying cuttings out from the bottom of the well.

Figure 6. Axial velocity distribution of annular fluid.

Figure 7 shows the inner streamline of annulus fluid at $z = 0.5m$ (the beginning of the spiral channel), 0.625m, 0.75m (the end of the spiral channel), 0.875m, 1m, 1.125 m, 1.25m and 1.375m respectively. It can be seen from the graph that, in general, with the increase of the number of grooves, the influence range of eddy current structure generated by spiral grooves becomes smaller. In terms of eddy current characteristics, it is also not conducive to cuttings removal.
To sum up, from the analysis results of static pressure, dynamic pressure, axial velocity and tangential velocity, it can be concluded that when the number of spiral grooves is 3, 4, 5 and 6 respectively, the spiral groove structure with the number of 3 has the best cleaning effect on cuttings bed.

3.2. Analysis of the influence of channel inclination on annular flow field
The inclination angle of the spiral groove will have an important influence on the cleaning effect of the spiral groove. In this paper, the inclination of spiral groove is changed by changing the parameter of lead. And the cleaning effect of spiral groove with different lead is also studied. Figure 8 is a schematic diagram of spiral grooves with different lead.

![Figure 8. Schematic diagram of spiral groove with different lead.](image)

Figure 9 and Figure 10 show that the hydrostatic and hydrodynamic profiles of annulus fluids are $z=0.5m$ (at the beginning of the spiral channel), 0.625m, 0.75m (at the end of the spiral channel), 0.875m, 1m, 1.125 m, 1.25m and 1.375m respectively.
Figure 9. Static pressure distribution of annular fluids.

(a) Lead = 500 mm

(b) Lead = 1000mm

Figure 10. Dynamic pressure distribution of annular fluids.

(a) Lead = 500 mm

(b) Lead = 1000mm

It can be seen that the fluctuation of hydrostatic and dynamic pressure in the radial direction of annulus fluid is relatively smaller when the lead of spiral groove is 1000mm. Not only in the spiral groove area and its vicinity, but also in many sections far from the groove. That is to say, when the lead of spiral groove is 1000mm, its stirring effect on annular fluid is relatively weak, and its cleaning effect is even weaker. The pressure distribution at the spiral groove can also be seen that when the lead is 1000mm, it is not conducive to the removal of cuttings compared with the 500 mm lead. Similar conclusions can be drawn from the analysis of Figure 11 and Figure 12. These two diagrams are the distributions of the axial and tangential velocities of annular fluid in the longitudinal section at x=0 under the action of helical groove structures with different lead. As shown in Figure 11, the overall axial velocity of annulus fluid decreases with the change of lead from 500 mm to 1000 mm, which will be detrimental to the carrying of cuttings. As can be seen from Figure 12, the larger the lead, the
smaller the tangential velocity of the annular fluid. In particular, the decrease of tangential velocity in small annulus will not be conducive to the substitution of cuttings into large annulus and its removal.

![Axial velocity distribution of annular fluid. Figure 11.](image)

![Tangential velocity distribution of annular fluid. Figure 12.](image)

From the above analysis data, it can be concluded that the spiral groove structure with 500 mm lead is more advantageous to the removal of cuttings bed than the spiral groove structure with 1000 mm lead.

3.3. Analysis of the influence of groove angle on annular flow field

In this paper, the cleaning effect of spiral groove with groove angles of 30 and 90 respectively is studied. Figure 13 is a schematic diagram of the groove angle of the spiral groove.
Figure 13. Drawing of groove angle

From Figure 14 and 15, it can be seen that compared with spiral grooves with 30 degrees groove angle, spiral grooves with 90 degrees groove angle will make the annular flow field have lower static pressure and higher dynamic pressure. As mentioned above, this will be more conducive to cuttings removal.

Figure 14. Static pressure comparison of annular flow field

Figure 15. Dynamic pressure comparison of annular flow field

From Figure 16 and 17, it can be seen that the spiral groove with 90 degree groove angle will make the annular flow field have higher axial and tangential velocities than the spiral groove with 30 degree groove angle, which is also more conducive to cuttings removal.

Figure 16. Axial velocity comparison of annular flow field
In conclusion, compared with the spiral groove with 30 degree groove angle, the spiral groove with 90 degree groove angle will make the annular flow field have better cleaning effect.

4. Conclusions
Through the numerical analysis of the annular flow field under the action of EHCDP, the following conclusions can be drawn:

1) Under the action of EHCDP, a strong swirl appears in the annular flow field, and a strong eddy appears near the spiral channel, which is beneficial to the removal of cuttings.
2) For drill pipes with spiral grooves of 3, 4, 5 and 6, the smaller the number of grooves, the greater the fluctuation of annular flow field. Moreover, all kinds of pressure and velocity analysis are more conducive to improving the removal effect of cuttings. That is to say, when the number of channel is 3, its cuttings removal effect is the best.
3) The spiral groove with 500 mm lead has a larger inclination angle than that with 1000 mm lead, which has a more obvious stirring effect on the flow field and better cuttings removal effect.
4) The spiral groove with 90 degree groove angle will make the annular flow field more conducive to cuttings removal than the spiral groove with 30 degree groove angle.

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