INTRODUCTION

In recent years, with the large-scale development of complex hydrocarbon reservoirs such as low permeability, unconventional, and deep water, horizontal and deviated well-drilling technology has become increasingly widely used. The application of horizontal well technology can significantly increase oil and gas production and ease the energy shortage problem. However, during the drilling process of horizontal and deviated wells, the cuttings that are removed by drilling bit are easily affected by gravity to form a cuttings bed at the bottom of the annulus with the drilling fluid circulation, and this is one of the biggest challenges during drilling. Insufficient hole cleaning will lead to safety problems such as high torque, high resistance, stuck pipe, and other risks. Therefore, the safe and effective removal of cuttings is of great significance in increasing drilling speed and reducing operating costs.

Cuttings transport is affected by many variables such as rotational speed of drill pipe (rpm), rate of penetration (ROP), wellbore structure characteristics (hole and drill pipe diameter, drill pipe eccentricity, well deviation...
angle, etc.), cuttings characteristics (size, density, and shape, etc.), and drilling fluids characteristics (fluid velocity, flow regime, mud type, mud rheological properties, etc.). Flow behavior of fluid and cuttings has been extensively investigated in well drilling. Although theoretically changing the above parameters can effectively alleviate the problem of hole cleaning, it is much restricted by engineering and cannot be changed at will. For example, increasing the fluid circulation velocity is one of the most reliable methods in the drilling industry to improve the efficiency of hole cleaning. However, the excessive flow rate will increase the pump pressure and increase the cost. It is more likely to damage the borehole wall and cause the wellbore erosion and lost circulation. Since the 2000s, wall and cause the wellbore erosion and lost circulation. It is more likely to damage the borehole wall and cause the wellbore erosion and lost circulation. Therefore, how to safely and effectively improve the hole cleaning ability and to prevent a series of adverse effects caused by the deposition of drilled cuttings is a thorny problem still now.

It is widely used in many industries to promote the transport velocity of the particles by inducing swirl flow in the pipe. Swirl flow is the flow form with velocity components in both axial and tangential directions. It has wide potential in many industrial applications. A variety of methods are commonly used to enhance the swirling effect of the fluid in the tube, including the spiral wall tangential inlet, and blades induction. Since the 2000s, field tests of several hole cleaning devices have shown its excellent hole cleaning ability. Puymbroeck et al introduced a compound hole cleaning device with double helix blade small joints. Laboratory experiments and field tests show that the device has an excellent cleaning ability of cuttings bed; besides, it improves the degree of hole cleaning by more than 60% and reduces the friction of drilling tools by 30%. Dave et al reported a blade-type hole cleaning device. Field experiment shows that it can effectively solve the problem of hole cleaning and poor wellbore quality. Heitmann et al reported a hole cleaning device with multi-cluster blades that were placed on the drill pipe. The field application shows that drilling time can be reduced by more than three days with the application of this device; the wearing of casing and bit is reduced effectively. It can be seen from the above work that it is an ideal hole cleaning method to induce swirl flow in the annulus by using drill pipe rotation to drive blade rotation, and one of its most significant benefits is that the rotational energy of the blade comes from the drill pipe, and no extra energy is needed. However, there are still some problems that need to be deeply studied. At present, the detailed study of the decay behavior of the swirl flow induced by the blade and the motion characteristics of drilled cuttings in the swirl flow is limited. The effect of changing some parameters on the hydrodynamic characteristics of the swirl flow is not completely clear. However, it is challenging to capture the microcosmic information of solid-liquid mixing through experiments.

The computational fluid dynamics (CFD) method has been rapidly developed as an effective tool to obtain the flow details of complex multiphase flow in a relatively short time. CFD has the great potential in predicting the flow characteristics and particle motion behavior in the swirling flow field. In this paper, the Eulerian-Eulerian two-fluid model and the Realizable $k$-$ε$ turbulence model are adopted and combined with the Sliding Mesh (SM) technology. The swirl flow that is induced by the blade of the hole cleaning device and the movement behavior of drilled cuttings in swirling flow is numerically analyzed. The effects of the rotational speed and the helical angle of the blade are investigated. The solid-liquid two-phase fluid was characterized regarding swirl strength and deposition index, and the effective distance and hole cleaning ability are evaluated. The research results are instructive to the design of the hole cleaning device that is using in the drilling engineering.

## 2 | METHODOLOGY

For solid-liquid two-phase flow, the Eulerian-Eulerian method regards granular phase and liquid phase as the continuous medium, which is more excellent than the Eulerian-Lagrangian approach method in computational cost and it can be accepted in engineering. In this paper, the Eulerian-Eulerian two-fluid model is used to study the flow. The continuum equation and the momentum equation applied to solid-liquid two-phase flow and the corresponding transport equations are obtained. The Realizable $k$-$ε$ turbulence model is used to introduce turbulence into the computational fluid dynamics model.

### 2.1 | Governing equations

The continuity equation of drilling fluid and cuttings are expressed as:

\[
\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l \bar{u}_l) = 0
\]  
\[1\]

\[
\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s \bar{u}_s) = 0
\]  
\[2\]

where, $l$ and $s$ are the representative indexes for drilling fluid and cuttings, respectively. $\alpha$ is the volume fraction. $\bar{\mathbf{u}}$ is the velocity vector. $\rho$ is the density. Each computational cell is shared by the interpenetrating phases so that the sum of their volume fractions is unity. The momentum equation for drilling fluid and cuttings can be expressed as:

\[
\frac{\partial}{\partial t}(\alpha_l \rho_l \bar{u}_l) + \nabla \cdot (\alpha_l \rho_l \bar{u}_l \bar{u}_l) = -\alpha_l \nabla p + \alpha_l \nabla \cdot \bar{\mathbf{r}}_l + \alpha_l \rho_l \bar{\mathbf{g}} - \beta (\bar{\mathbf{u}}_l - \bar{\mathbf{u}}_s)
\]  
\[3\]
\[
\frac{\partial}{\partial t}(\alpha_s \rho_s \mathbf{u}_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{u}_s \mathbf{u}_s) = -\alpha_s \nabla p - \nabla p_s + \alpha_s \nabla \cdot \mathbf{T}_s + \alpha_s \rho_s \mathbf{g} + \beta(\mathbf{u}_s - \mathbf{u}_l)
\]

where \( \mathbf{g} \) is the acceleration due to gravity, \( \mathbf{T} \) is the stress tensor, \( p \) is the pressure shared by all the phases, \( p_s \) is the solid pressure. \( \beta \) is the interface momentum transfer coefficient which is given by the Huilin-Gidaspow drag model. \(^{25}\) The Gidaspow model \(^{26}\) is a combination of the Ergun model \(^{27}\) and the Wen and Yu model. \(^{28}\) For liquid concentrations greater than 0.8, momentum exchange coefficient \( \beta \) between liquid and solid is determined by the Ergun model. However, the drag function of the Gidaspow model is discontinuous with the change of the solid volume fraction, which is contrary to the physical law. The drag force is a continuous function of the solid phase volume fraction and Reynolds number. Therefore, Huilin-Gidaspow model is proposed to correct the discontinuity of drag function. In this model, the momentum exchange coefficient between liquid and solid is as follows:

\[
\beta_{\text{Huilin-Gidaspow}} = \varphi \beta_{\text{Ergun}} + (1 - \varphi) \beta_{\text{Wen&Yu}}
\]

\[
\varphi = \frac{\arctan \left[ 262.5(\alpha_s - 0.2) \right]}{\pi} + 0.5
\]

When \( \alpha_s \leq 0.8 \),

\[
\beta_{\text{Ergun}} = 150 \frac{\alpha_s (1 - \alpha_s) \mu_l}{\alpha_l d_s^2} + 1.75 \frac{\rho_l \alpha_s |\mathbf{u}_s - \mathbf{u}_l|}{d_s}
\]

When \( \alpha_s > 0.8 \), the fluid-particle exchange coefficient is calculated as:

\[
\beta_{\text{Wen&Yu}} = \frac{3}{4} C_D \frac{\alpha_s \alpha_l \mu_l}{d_s} |\mathbf{u}_s - \mathbf{u}_l|^{-2.65}
\]

where the drag coefficient, \( C_D \), is

\[
C_D = \frac{24}{Re_s} \left( 1 + 0.15 Re_s^{0.687} \right) \text{ for } Re_s \leq 1000
\]

\[
C_D = 0.44 \text{ for } Re_s > 1000
\]

where the Reynolds number for cuttings phase is defined as:

\[
Re_s = \frac{\rho_l d_s |\mathbf{u}_s - \mathbf{u}_l|}{\mu_l}
\]

\[
\mathbf{u}_l = \mu_s \left\{ \left[ \nabla \mathbf{u}_l + (\nabla \mathbf{u}_l)^T \right] - \frac{2}{3} \left( \nabla \cdot \mathbf{u}_l \right) \mathbf{I} \right\}
\]

\[
\frac{\partial}{\partial t}(\alpha_s \rho_s \mathbf{u}_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{u}_s \mathbf{u}_s) = -\alpha_s \nabla p - \nabla p_s + \alpha_s \nabla \cdot \mathbf{T}_s + \alpha_s \rho_s \mathbf{g} + \beta(\mathbf{u}_s - \mathbf{u}_l)
\]

where \( \mathbf{g} \) is the unit vector, \( \mu_l \) and \( \mu_s \) are fluid viscosity and shear viscosity of drilled cuttings. \( \xi_s \) is the solids viscosity. Solid pressure \( p_s \) is defined as

\[
p_s = \alpha_s \rho_s \Theta_s + 2 \rho_l (1 + e) \alpha_s^2 g_0 \Theta_s
\]

While \( e \) is the restitution coefficient of particle collisions, \( \Theta_s \) is the granular temperature, and \( g_0 \) is the radial distribution function which is modeled as below:

\[
g_0 = \left[ 1 - \left( \frac{\alpha_s}{\alpha_{\text{max}}} \right)^{0.5} \right]^{-1}
\]

The solid shear viscosity \( \mu_s \) can be expressed by

\[
\mu_s = \frac{4}{3} \alpha_s \rho_s d_s g_0 (1 + e) \sqrt{\frac{\Theta_s}{\pi}} + \frac{10 \rho_l d_s \sqrt{\pi} \Theta_s}{96(1 + e) \alpha_s g_0} \left[ 1 + \frac{4}{5} g_0 \alpha_s (1 + e) \right]^2
\]

The transport equation of granular temperature (algebraic formulation) derived from kinetic theory takes the form:

\[
0 = (-p_s \mathbf{I} + \mathbf{c} \cdot \nabla) \mathbf{u}_s - \gamma_{\Theta_s} + \phi_{\Theta_s}
\]

where \( (-p_s \mathbf{I} + \mathbf{c} \cdot \nabla) \mathbf{u}_s \) is the generation of energy by the solid stress tensor, \( \gamma_{\Theta_s} \) is the collisional dissipation of energy, and \( \phi_{\Theta_s} \) is the energy exchange between the fluid and solid phase.

For the present study, it has been found that Realizable \( k-\epsilon \) model is more accurate than all of the \( k-\epsilon \) models, especially for separated flows, boundary layer flows involving high pressure gradients, and flows with complex flow structures, and this makes it suitable for the current problem. \(^{29}\) The modeled transport equations for turbulence kinetic energy (TKE), \( k \), and its dissipation rate, \( \epsilon \), in the Realizable \( k-\epsilon \) model are expressed as follows:

\[
\frac{\partial (\rho_s k)}{\partial t} + \frac{\partial (\rho_s k u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \left( \mu_s + \frac{\mu_s \sigma}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right) + G_k - \rho_s \epsilon
\]

\[
0 = \frac{\partial (\rho_s \epsilon)}{\partial t} + \frac{\partial (\rho_s \epsilon u_i)}{\partial x_j} - \frac{\partial}{\partial x_j} \left( \left( \mu_s + \frac{\mu_s \sigma}{\sigma_k} \right) \frac{\partial \epsilon}{\partial x_j} \right) + \rho_s C_{1\epsilon} \epsilon - \rho_s C_{2\epsilon} \frac{\epsilon^2}{k + \sqrt{\rho_s \epsilon}}
\]
\[ G_k = \mu_S S^2 \]  \hspace{1cm} (21)
\[ \mu_l = \rho_l C_{\mu} \frac{k^2}{\varepsilon} \]  \hspace{1cm} (22)

where \( C_\mu \) is a function related to the average changed rate and turbulent flow field, and \( S \) is the modulus of the mean rate of strain tensor, and defined as:

\[ S = \sqrt{2S_{ij}S_{ij}} \quad \text{and} \quad S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]  \hspace{1cm} (23)

The coefficients that appeared in the above Realizable \( k-\varepsilon \) equations are as following, \( C_1 = \max \left[ 0.43, \frac{\varepsilon}{\eta \tau} \right] \), \( \eta = S^2 \); \( \sigma_k = 1.0 \), \( \sigma_\varepsilon = 1.2 \), and \( C_2 = 1.9 \).

### 2.2 Model geometry and boundary conditions

In this study, the three-dimensional calculation region is a concentric annulus composed of drill pipe and wellbore, and the computational domain has the same geometric size as the experiment of Han et al. The hole cleaning device is simulated by simplified blades. In the single-phase case, the length of the inlet section of turbulent flow \( L_e \) is calculated by Munson to ensure that the fluid is in the complete development stage before entering the area of the blade.

\[ L_e = 4.4D_h (R_e_D)^{1/6} \]  \hspace{1cm} (24)
\[ R_e_D = \frac{\rho_l U_{in} D_h}{\mu_l} \]  \hspace{1cm} (25)

where \( R_e_D \) is the Reynolds number, \( D_h \) is the hydraulic diameter, and \( U_{in} \) is the axial velocity. Based on the above formula, the length of the inlet section is calculated. By calculation, the blade is placed at a distance of 0.4 m from the entrance, the length of the blade is 0.1 m, and the number of blades is four. The geometry of the blade depends on the height, angle, number, and length of the blade. However, for this study, the discussion on blade structural parameters will be limited to the helical angle of the blade, and other parameters such as blade height are selected as constant values. This is because the increase of blade height can improve the ability to induce swirl flow, but the design of the blade height is not allowed to be too large in a complex downhole environment, so the blade height is not taken into account. At the same time, in order to observe the decay phenomenon of the swirl flow directly, ignore the shear force that is applied to the fluid by the rotation of the drill pipe and only the influence of blade rotation is considered. Table 1 lists the geometrical parameters and operating conditions used in these simulations.

### 2.3 Simulation strategy

The finite volume method is used for the discretization of the governing equations, and the Phase Coupled SIMPLE scheme is applied to the pressure-velocity coupling. The momentum equations are discretized using the QUICK scheme due to its good performance on the hexahedral mesh. The relative error between two successive iterations is specified through the use of a convergence criterion of \( 10^{-5} \) for each scaled residual component. A time step of 0.001 s with 20 iterations per time step is chosen.

**Table 1** Geometrical parameters and operating conditions in the numerical simulation

| Parameter                        | Value       |
|----------------------------------|-------------|
| Drill string length, L (m)       | 1.8         |
| Angle of inclination, \( \theta \) (deg) | 60          |
| Drill pipe diameter, \( D_h \) (mm) | 30          |
| Hole diameter, \( D_1 \) (mm)     | 44          |
| Eccentricity \( e \)              | 0           |
| Drill pipe rotational speed, \( n_0 \) (rpm) | 80, 120, 160, 200 |
| Fluid inlet velocity, \( U_{in} \) (m/s) | 1.02        |
| Fluid density, \( \rho_l \) (kg/m³) | 998.5       |
| Fluid viscosity, \( \mu_l \) (Pa·s) | 0.001       |
| Particle density \( \rho_p \) (kg/m³) | 2550        |
| Particle diameter, \( d_i \) (mm) | 1           |
| Injected particle volume fraction \( C_v \) (%) | 4           |
| Helical angle \( \alpha \) (deg) | -30, -20, -10, 0, 10, 20, 30 |
| Blade height \( h/D_h \)         | 0.25        |
the simulations in this work are performed on the Core i7 processor with 8 cores and a total memory size of 16 GB RAM.

### 2.4 Computational mesh and grid independence study

Since grids of different sizes have a great influence on simulation results, grid independence testing is significant in CFD simulation. For this reason, four geometric models with different mesh sizes are selected for CFD simulation. Table 2 shows the simulation results of four different grid resolutions, and it can be seen from Table 2 that for grid size increases to 437 828 and 553 028, and it is clear that their predicted values are very close, which indicates that in a given grid division, the simulation results almost no longer change with the increase of mesh. Therefore, in this paper about 440 000 hexahedral elements are generated for analyzing the swirl flow field.

The grid of the hole cleaning device is generated by using structured hexahedral elements with the grid partitioning method. The grid cells near the blade are refined, and the near wall treatment was a standard wall function. Figure 2 shows the computational grids of the geometry model.

### 3 RESULTS AND DISCUSSION

#### 3.1 Model validation between simulations and experiments

In order to attain confidence from the simulation results, the simulation results are compared with the experimental results in the literature. Two simulations are performed, one...
to observe the decaying swirl flow along the flow direction under single-phase fluid conditions and the other to observe the average transport velocity of the particles under solid-liquid two-phase conditions.

The swirl number $S_n$ is usually used to characterize the magnitude of swirl intensity and the effect of swirl on particle deposition. Swirl number $S_n$ is a dimensionless parameter, which was first proposed by Chigier and Beer. It is defined as the ratio of the axial flux of angular momentum to the axial flux of axial momentum on the desired surface:

$$S_n = \frac{\int_{R_0}^{R_1} \frac{u_0 \omega^2}{\mu} dr}{\int_{R_0}^{R_1} \frac{u^2}{\mu} rdr}$$

(26)

where $R_1$ and $R_0$ represent the radius of the wellbore and drill pipe, respectively. It is shown that the swirl number $S_n$ of swirling flow in the pipe agrees with the exponential distribution along the axial direction due to the friction loss of the pipe wall and the viscous shear effect of the fluid. It is shown that the $S_n$ is positive when the rotation direction of swirl flow is consistent with the rotation direction of the blade; conversely, $S_n$ is negative.

The decay of the swirl flow can be evaluated by the decay rate $\beta$, which is the primary parameter to study the swirl flow. The decay law of swirl intensity can be expressed by the following formula:

$$S_n = S_0 \exp \left( -\frac{L}{\beta D_h} \right)$$

(27)

In the equation, $L$ is the distance behind the blade; $\beta$ is the magnitude of the decay rate; and $S_0$ is the initial swirl intensity.

Figure 3A shows the distribution of the dimensionless swirl intensity $S_n/S_0$ along the flow direction compared with the experimental results from Fokeer, and Figure 3B shows the change of average particle transport velocity with different drilling fluid velocity under the solid-liquid two-phase condition compared with the experimental results from Han. The results show that the model can accurately predict the decay behavior of the swirl flow and the particle behavior in solid-liquid two-phase flow, and the numerical
simulation results are in good agreement with the available experimental data.

3.2 Effect of rotational speed on hole cleaning performance

During the rotation of the blade, the mechanical energy of the blade can be transferred to the fluid, and the increase of the rotational speed of the blade can make the fluid obtain more tangential kinetic energy. Figure 4 shows the decay behavior of the swirl number $S_n$ along with the flow direction in single-phase condition at $\alpha = 0^\circ$. As expected, it is observed that the swirl flow exponentially decays along the flow direction, and this result is consistent with the experimental observations$^{14,32,33}$; the decay equation is obtained by fitting the curve. The results show that the initial swirl strength $S_0$ increases with the increase of the rotational speed, but at a high rotational speed, the swirl intensity gain caused by the increased rotational speed gradually decreases. For each increase of 40 rpm at 80 rpm, 120 rpm, and 160 rpm, the initial swirl intensity increases by 75.9%, 46.4%, and 33.3%, respectively, indicating that the increase of rotational speed at high speed is not as obvious as that at the low rotational speed. At the same time, it can be seen from the fitting equation that the decay rate $\beta$ of swirl flow is smaller at a high rotational speed, and the decay rate $\beta$ of 200 rpm is about 10.3% higher than that of 80 rpm. This is because the decay rate $\beta$ is a function of the friction coefficient $f$, and at a high rotational speed, the swirl flow resists wall friction and the shear loss that is caused by fluid viscosity is bigger$^{34,35}$.

Figure 5 shows the tangential velocity of the particles in the dimensionless radial position when the helical angle is $\alpha = 0^\circ$ at $z = 0.6$ m. The results show that the distribution of tangential velocity on both sides is asymmetric, and the profile of tangential velocity distribution is similar to that of a Rankine vortex. The increase of rotational speed will result in a centrifugal effect on particles, which will result in the increase of tangential velocity of particles in annulus$^{36}$. For example, at 200 rpm, the maximum tangential velocity of the particles can reach 0.2 m/s, which is about 0.75 times larger than that of 80 rpm. The velocity distributions on both sides are different because the particles are affected by the different mass forces in different radial directions. At the same time,
the tangential velocity of particles decreases to 0 at the wall and reach the maximum in the central region of the annulus, which indicates that the swirling effect of the fluid in the central region of the annulus is stronger and the tangential kinetic energy of the fluid is larger. Under the action of this high tangential velocity, the deposition tendency is greatly alleviated and the cuttings transport capacity improved.

In order to capture the macroscopic flow behavior of particles, Figure 6 shows the flow of cuttings along the flow direction when the helical angle is $\alpha = 0^\circ$. The drilled cuttings and drilling fluid are injected into the annulus at the entrance and gradually accumulated at the bottom of the annulus as the flow proceeded. After passing through the blade, because of the disturbance of the blade and the swirling effect of the swirl flow, the drilled cuttings are subjected to a tangential force under the rotating action of the blade, thus avoiding the deposition at the bottom of the annulus. With the continuation of the flow, the swirling effect weakens and the tangential kinetic energy of the particles decreases gradually and deposits gradually at the bottom of the annulus. From the distribution of cuttings volume fraction, it can be seen that the flow of cuttings can be divided into three regions, the suspension region, the moving bed region, and the fixed bed region, consistent with experimental observations.37

In order to evaluate the ability of particles to resist deposition under the action of swirl flow and the influence of different blade parameters on the hole cleaning ability. A new deposition index is proposed in this work to quantify the cuttings deposition in annulars:

$$\text{Deposition index } \sigma = 1 - \frac{C_{V,up}}{2 \times C_V}$$  \hspace{1cm} (28)

where $C_{V,up}$ respect the cuttings concentration in the upper half of the selected cross section, and $C_V$ is the cuttings concentration of the selected cross section. From the definition of parameters, a better degree of hole cleaning will be obtained at a lower $\sigma$. Figure 7 shows the distribution curve of the deposition index along the flow direction with four rotational speeds. Compared with the case without the blade, the phenomenon of cuttings deposition is alleviated when with rotational blades, and with the increase of rotational speed, the effective distance of swirl flow in annulus increases gradually. At 200 rpm, the expected effective distance of the blade with helical angle $\alpha = 0^\circ$ can exceed 0.95 m, while an additional serious deposition phenomenon is found where the swirling effect is about to disappear, and the deposition phenomenon is slightly alleviated and stabilized after a brief existence. This is the local dune flow phenomenon of the moving bed region caused by the weakening of the swirling effect.38

Figure 8 shows the profiles of cuttings volume fraction at $z = 1.0$ m with four rotational speeds. The swirl intensity decreases gradually along the flow direction, and the tangential kinetic energy transferred to the particles decreases at a certain rotational speed. With the increase of rotational speed, the deposition of cuttings is gradually alleviated at the same cross section. At the same time, it can be observed that at a high rotational speed, such as 120 rpm, 160 rpm, and 200 rpm, a certain degree of deflection occurs in the deposition of cuttings at the bottom of the annulus, and the greater the rotational speed is, the more obvious the deflection is. This is precisely the swirl flow effect that changes the deposition distribution of drilled cuttings at the bottom of the annulus. It is consistent with the swaying phenomenon obtained from experimental results by Tomren et al.4

![FIGURE 6](image)

**FIGURE 6** The flow of cuttings along the flow direction with different rotational speed

![FIGURE 7](image)

**FIGURE 7** Deposition index distribution along with the flow direction with different helical angle
3.3 Effect of helical angle on hole cleaning performance

Under the action of rotation, the change of the helical angle of the blade will directly affect the flow direction of the fluid, which is another important parameter affecting the hole cleaning efficiency of the hole cleaning device. Figure 9 shows the decay behavior of the swirl number along with the flow direction in single-phase condition with different helical angles when the rotational speed is 120 rpm. It can be seen that under the action of different helical angles, all the curves of the swirl flow decay exponentially along the flow direction. As seen from Figure 9, the positive blade at $\alpha = 20^\circ$ and $\alpha = 30^\circ$, it shows that the rotation direction of the swirl flow has changed and it is opposite to the rotation direction of the blade. The reason for this flow pattern change is that the
deflection angle of the swirl flow is affected by the rotation of the blade and the forced deflection of the helical angle, which can lead to the deflection of the fluid. As shows in Figure 1b, when the two satisfy the following formula, the flow direction of the swirl flow induced by the blade will not deflect, and the flow will become an axial flow.

\[ \psi = \arctan \left( \frac{n_0 \pi D_0}{60 U_{in}} \right) \]  (29)

where \( n_0 \) is the rotational speed per minute for the blade. The critical angle \( \psi \) was 10.47° under the parameter settings of this article. For the positive blade, changing some parameters makes the fluid deflection angle approach the axial flow, which is an unfavorable phenomenon, because the swirling effect of near-axial flow will decrease sharply, and the hole cleaning effect will be very poor. This unfavorable phenomenon does not occur when the helical angle is changed for the negative blade.

In order to evaluate the initial swirl intensity \( S_0 \) distribution of different helical angles, as shown in Figure 10, the initial swirl intensity \( S_0 \) distribution under seven different helical angles is obtained and fitted. It can be seen that the initial swirl intensity increases with the decrease of helical angle, and the rotating direction of the swirl flow changes when the helical angle exceeds the critical value, which is opposite to the rotating direction of the blade. The fitted critical helical angle is 10.91°, which is about 4.2% different from the predicted value. The results show that for the positive blade, the helical angle may approach the critical helical angle \( \psi \) when the drilling parameters are changed. If possible, the design should be avoided as far as possible.

Figure 11 shows the tangential velocity distribution curve of the particles at \( z = 0.6 \) m with different helical angles. It can be seen from the figure that the distribution of the tangential velocity in the radial direction at different helical angles is also asymmetrical. It is also observed that the tangential velocity profile of the particle is similar to that of Rankine vortex.

As seen from Figure 11A, due to the worst swirling effect of the positive blade with helical angle \( \alpha = 10^\circ \), the swirl flow is near-axial flow. Under the action of gravity, the tangential velocity of the particles is distributed in opposite directions at different radial positions. For the positive blade with helical angle \( \alpha = 20^\circ \) and \( \alpha = 30^\circ \), with the increase of helical angle, the distribution of Rankine vortex is gradually obvious, and the tangential velocity distribution is all negative. This is the result of a change in the direction of rotation of the swirl flow. As seen from Figure 11B, the tangential velocity value of the particles increases with the decrease of helical angle. For example, at the positive blade with helical angle \( \alpha = -30^\circ \), the maximum tangential velocity is about 54.1% higher than that with \( \alpha = -10^\circ \). The results show that the swirl flow induced by the negative blade has higher tangential kinetic energy, and it is easier to overcome the adverse effect of gravity.

Figure 12 shows the flow of cuttings along the flow direction with different helical angles when the rotational speed is 120 rpm. The results show that the position at which the drilled cuttings re-deposit is related to the magnitude of the swirling intensity, and the hole cleaning effect of the negative blade is better than that of the positive blade. For the negative blade, the initial swirl intensity \( S_0 \) of the swirl flow induced by the blade is higher, so all the three helical angles have a good hole cleaning effect.
effect. However, for positive blade the flow deflection angle is close to axial flow at helical angle $\alpha = 10^\circ$, so the hole cleaning effect is the worst. When the helical angle is larger than the critical angle $\psi$, the hole cleaning effect increases gradually with the helical angle increasing to $\alpha = 20^\circ$ and $\alpha = 30^\circ$.

Figure 13 shows the distribution curve of the deposition index along the flow direction with different helical angles. As seen from Figure 13A, the deposition index obtained from the positive blade with helical angle $\alpha = 10^\circ$ and $\alpha = 20^\circ$ is not ideal, and the deposition index is improved to a great extent at helical angle $\alpha = 30^\circ$. This indicates that the cuttings transport in the cuttings bed should satisfy at least one critical swirl number. Otherwise, increasing the swirl strength of the fluid within the critical swirl number will not help the hole cleaning. At the same time, it can be seen from Figure 13B that the distribution of deposition index with the three helical angles for the negative blade is ideal, and the average effective distance can exceed 1.1 m. The results show that the hole cleaning effect of the negative blade is better than that of the positive blade.

Figure 14 shows the profiles of cuttings volume fraction at $z = 1.0$ m under different helical angles. It can be seen from the figure that the deposition of drilled cuttings is greatly alleviated under the action of the negative blade with three different helical angles. Moreover, the cuttings were distributed counterclockwise at the bottom of the annulus. It was found that for the positive blade with helical angle $\alpha = 10^\circ$ and $\alpha = 20^\circ$, the depositional phenomenon of drilled cuttings is very serious, most of the drilled cuttings are deposited at the bottom of the annulus, and the deposition is alleviated under the action of the positive blade with helical angle $\alpha = 30^\circ$. Moreover, the deposition direction of the cuttings at the bottom of the annulus becomes clockwise, which indicates that when the choice of the helical angle is greater than the critical value, it does affect the direction of rotation of the swirl flow, and thus, the direction of deposition of the cuttings at the bottom of the annulus is changed.

4 | CONCLUSION

The Eulerian-Eulerian two-fluid model and Realizable $k-\varepsilon$ turbulence model are adopted and combined with Sliding
Mesh (SM) technology. This paper mainly studies the effects of the helical angle and the rotational speed of the blade of the hole cleaning device on the swirl strength of decaying swirl flow and drilled cuttings deposition behavior. The model validity is confirmed by previous experimental studies, and the conclusions can be obtained as follows:

1. The swirl intensity of the swirl flow exponentially decays along the flow direction, and the decay rate \( \beta \) is related to the friction coefficient. The rotational speed of the blade has a significant effect on the swirling flow field. With the increase of rotational speed, the tangential kinetic energy of the swirling fluid is increased, so that the tangential kinetic energy of particles is increased, the deposition of particles is alleviated, and the hole cleaning efficiency is improved.

2. There is a critical helical angle \( \psi \) under certain drilling operation parameters. The initial swirl intensity \( S_0 \) of swirl...
flow increases with the decrease of helical angle $\alpha$, and the rotational direction of the swirl flow has changed when the helical angle exceeds the critical value.

3. The results show that the hole cleaning effect of the negative blade is better than that of the positive blade, and the positive blade shows poor hole cleaning effect when the helical angle approaches the critical angle $\psi$.

4. The greater the swirl intensity of the swirl flow, the stronger the degree of suspension of drilled cuttings in the annulus, but the movement of the cuttings needs to satisfy a certain critical swirl number to start. The swaying phenomenon can be seen at the bottom of the annulus, and with the increase of the swirl intensity, the trend can be more obvious, and the deposition direction of the drilled cuttings is affected by the direction of the swirl flow.

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