

Effect of drillpipe rotation on cuttings transport using computational fluid dynamics (CFD) in complex structure wells

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Abstract Effective cuttings transport is one of the most major concerns in designing hydraulic parameters during drilling complex structure wells. It is important and essential to study critical parameters how to influence cuttings bed development, especially the drillpipe rotation effects on cuttings transport behavior. In this study, cuttings transport simulations were carried out for inclinations from 45° to 90°, for pipe rotation speeds from 80 to 240 rpm, and for flow rates from 30 to 50 L/s. Annular cuttings volume, pressure drop, and cuttings distribution are recorded simultaneously within the simulation proceeding. The CFD simulations show that pipe rotation makes cuttings presented in asymmetric distribution along the wellbore and significantly improves the drag effects on drilling fluid in the tangential direction. At a low or medium flow rate, pipe rotation has a significant impact on annular cuttings volume and pressure drop. However, there is no additional contribution of pipe rotation after reaching critical speed at high flow rates. Buckingham- π theorem combined with least square method was applied to establish the empirical correlations for estimating cuttings concentration and annular pressure drop.

Keywords CFD · Hole cleaning · Cuttings transport · Drillpipe rotation · Complex structure well

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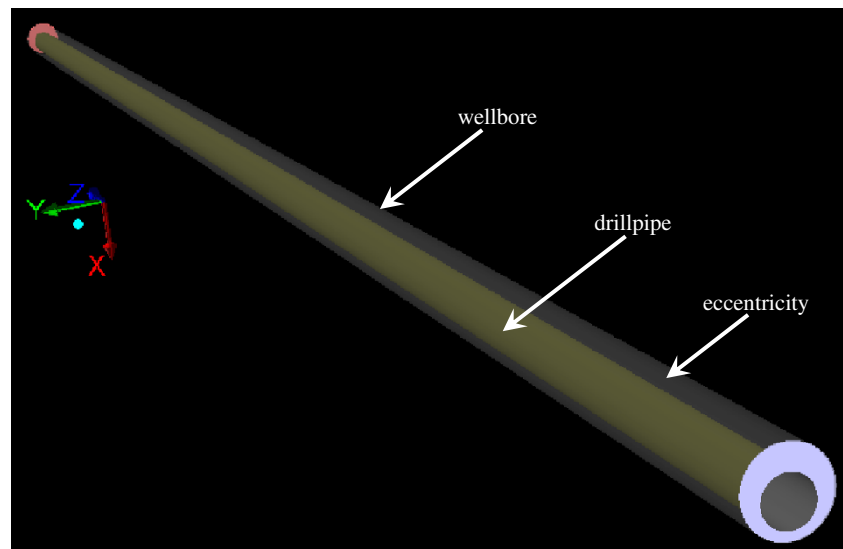
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Introduction

Complex structure well includes horizontal well, extended reach well, and multilateral well, which has been widely used for offshore oil exploration and exploitation and improving the recovery of oil field. However, hole cleaning is often difficult to be handled during drilling inclined and horizontal sections of complex structure wells, and cuttings are easily accumulated to develop cuttings bed, especially in the inclinations around 40°–60°, which may lead to various problems such as high drag and torque, pipe stuck, weight stacking, higher hydraulic requirements and excessive ECD, and cementing issues. Therefore, it is important and essential to study the key factors of cuttings bed development in annulus, especially if drillpipe is rotating. Numerous researches related to the effect of pipe rotation on hole cleaning have been carried out by experimental investigations and CFD simulations in the past several years.

In experimental investigations, Peden et al. (1990) observed that pipe rotation has a significant effect on the minimum transport velocity in medium or highly viscous fluids and contributes to cuttings transport in small annulus or positive eccentricity. Sifferman et al. (1992) pointed out that drillpipe rotation reduces annular cuttings buildup under certain conditions, and the effect is greatest at inclination near horizontal, for small cuttings and low rate of penetrations. Bassal (1996) indicated pipe rotation enhances hole cleaning more when the used mud has a higher viscosity with smaller cuttings sizes or for hole angle at 65°. Sanchez et al. (1999) analyzed the effects of pipe rotation–flow rate, pipe rotation–mud rheology, pipe rotation–inclination, and pipe rotation–cuttings size. The results show that in lower inclinations, no critical range of rotary speeds is determined but higher meant better, and orbital motion

Fig. 1 Physical model of inclined section



can significantly improve cuttings transport. Duan et al. (2008) performed the experiments about different cuttings sizes under pipe rotation. It was observed that small cuttings transport is mainly dominated by pipe rotation and fluid rheology, and improvement by pipe rotation in the transport efficiency of small cuttings is up to twice as large as the improvement in large cuttings transport. Ozbayoglu et al. (2008) and Sorgun (2010) indicated pipe rotation has a significant improvement on cuttings transport, especially when the pipe is making an orbital motion. But drillpipe rotation has no additional contribution to hole cleaning after a certain rotation speed. Also, the empirical correlations for 60°–90° were developed for predicting the stationary cuttings bed height and frictional pressure drop.

In CFD simulations, Bilgesu et al. (2002, 2007) were one of the first researchers to analyze cuttings transport parameters using CFD. The simulations show drillpipe rotation can improve the cuttings transport, and the effect is more pronounced for smaller particle size. Mishra (2007) found that hole cleaning efficiency is improved more significantly for small cuttings than for large cuttings as pipe rotation is increased, and pipe rotation at a fixed velocity can decrease pressure loss. Wang et al. (2009) indicated the solid flow becomes favorable, and the solid volume is reduced with the increase of rotary speeds. The correlation was also developed to estimate cuttings bed height. Li et al. (2010) found that pipe rotation between 80 and 120 rpm has a significant effect on hole cleaning.

Although some achievements have been made, but the pipe rotation effects on cuttings transport are difficultly be accurately depicted due to the complexity of cuttings–fluid coupling. The purpose of this paper mainly further discussed the cuttings transport behavior with pipe rotation using CFD.

Physical model of inclined section

Complex structure well usually contains the two or three buildup sections. The 215.9 mm wellbore diameter and 127 mm outer diameter of drillpipe are adopted to simulate the actual annulus. A 12-m-long interval is simulated without considering borehole enlargement and shrinkage. The eccentricity is 0.5, and eccentric distance is 44.45 mm. The gravity effect, horizontal and vertical vibrations are also considered, and the diagram of the physical model is shown in Fig. 1.

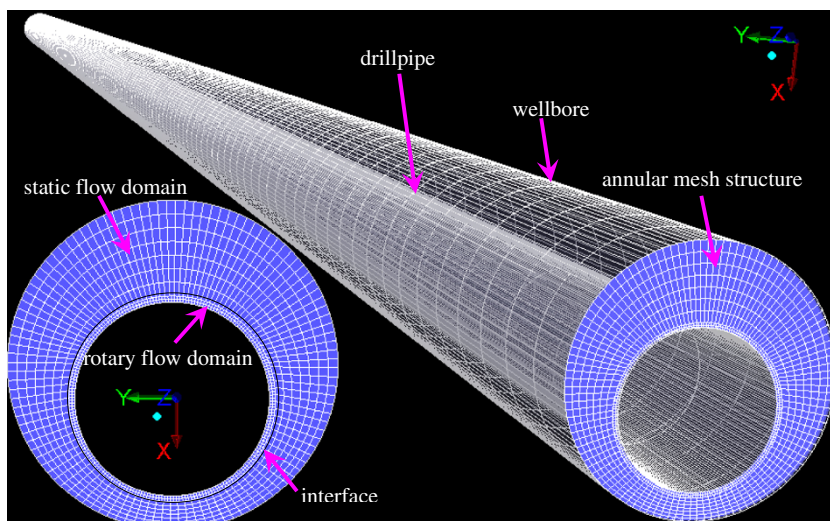
Gridding

To simulate the effect of drillpipe rotation on transient cuttings transport in annulus, moving mesh is applied for the flow domain in annulus. As shown in Fig. 2, all the annulus can be divided into both outer and inner flow domain. The flow domain near drillpipe is rotating with a certain speed to simulate the pipe rotation effect, and the outer flow domain is static. In addition, inner flow domain transfers pressure, velocity, cuttings concentration, and other parameters through interface.

Mathematical model of CFD simulations

To observe the effect of different rotation speeds on the drilling fluid–cuttings two-phase flow behavior, the Euler multiphase flow in rotary coordinate system is chosen as the simulated model. Standard function is used to calculate the momentum equation for low Reynolds number zone near drillpipe surface. The momentum equation for fully turbulent zone is determined by Realizable k - ε model (Shih

Fig. 2 Side view and profile of annular grid structure



et al. 1995). Also, first order upwind scheme of finite volume method is applied to discretize the governing equations, and the value that settling cuttings volume in annulus tends to be stable is considered as convergence criterion. These governing equations can be listed as follows:

Mass equation of liquid phase:

$$\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l \vec{v}_l) = \Delta m_{sl} \tag{1}$$

Mass equation of solid phase:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s) = \Delta m_{ls} \tag{2}$$

Momentum equation of liquid phase:

$$\begin{aligned} \frac{\partial}{\partial t}(\alpha_l \rho_l \vec{v}_l) + \nabla \cdot (\alpha_l \rho_l \vec{v}_l \vec{v}_l) + \rho_l (2\vec{\omega} \times \vec{v}_l + \vec{\omega} \times \vec{\omega} \times \vec{r}) \\ = -\alpha_l \nabla p + \mu \nabla^2 \vec{v}_l + \alpha_l \rho_l \vec{g} \\ + K_{sl}(\vec{v}_s - \vec{v}_l) + \Delta m_{sl} \vec{v}_{sl} - \Delta m_{ls} \vec{v}_{ls} \end{aligned} \tag{3}$$

Momentum equation of solid phase:

$$\begin{aligned} \frac{\partial}{\partial t}(\alpha_s \rho_s \vec{v}_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s \vec{v}_s) + \rho_s (2\vec{\omega} \times \vec{v}_s + \vec{\omega} \times \vec{\omega} \times \vec{r}) \\ = -\alpha_s \nabla p + \mu \nabla^2 \vec{v}_s + \alpha_s \rho_s \vec{g} \\ + K_{sl}(\vec{v}_l - \vec{v}_s) - \Delta m_{sl} \vec{v}_{sl} + \Delta m_{ls} \vec{v}_{ls} \end{aligned} \tag{4}$$

where “s” and “l” are the subscripts that represent solid and liquid-phase parameter. Δm_{sl} is that the mass transfers from solid phase to fluid phase. Similarly, the position exchange of subscript indicates the mass transfers from fluid phase to solid phase. Also, $\Delta m_{sl} = -\Delta m_{ls}$; v_{ls} is the velocity between phases. When $\Delta m_{ls} > 0$, $v_{ls} = v_{sl}$. When

$\Delta m_{ls} < 0$, $v_{ls} = v_s$ and $v_{ls} = v_{sl}$; α is the phase volume fraction; K_{sl} is the solid–liquid momentum interchange coefficients, and $K_{sl} = \alpha_s \rho_s f / \tau_s$. τ_s is the relaxation time of particles, and $\tau_s = \rho_s d_s^2 / (18 \mu)$. Here, $K_{ls} = K_{sl}$, and f which can be obtained from Syamlal–O’Brien model (Syamlal et al. 1989) is the function of drag force.

Boundary conditions and initial conditions

Boundary conditions of the transient simulation apply velocity inlet and pressure outlet, and setting different values of inlet velocity and outlet pressure can be used to simulate the different rotation speeds and well depths, respectively. The density of drilling fluid is 1,200 kg/m³, and the viscosity is 30 mPa s. Cuttings density is 2,500 kg/m³, and the diameter is 8 mm. The volume fraction of cuttings is 1 %. The simulations are divided into 12 groups, and the more detailed parameters are shown in Table 1.

Results and discussions

Effects of pipe rotation on velocity profile

The purpose of analyzing the velocity profile is that the effects of pipe rotation on annular pressure drop are actually caused by redistribution in annulus. The redistribution of velocity also has a significant effect on cuttings transport. As shown in Fig. 3, CFD simulations show that tangential velocity is decreases by exponential function along the tangential direction and the ratio of reduction become small with the increase of rotation speed. It is generally considered that the tangential velocity of drilling fluid is

Table 1 The variables required by CFD simulations

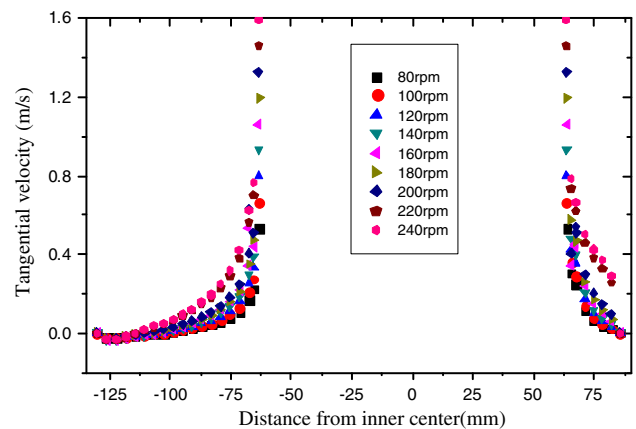
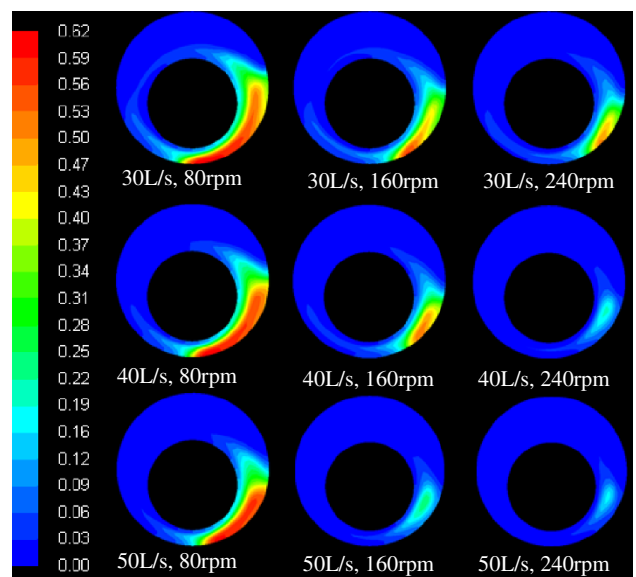
Groups	Inclination (°)	Flow rate (L/s)	Pipe rotation speed (rpm)
1–9	45	30	80, 100, 120, 140, 160, 180, 200, 220, 240
10–18	45	40	80, 100, 120, 140, 160, 180, 200, 220, 240
19–27	45	50	80, 100, 120, 140, 160, 180, 200, 220, 240
28–36	60	30	80, 100, 120, 140, 160, 180, 200, 220, 240
37–45	60	40	80, 100, 120, 140, 160, 180, 200, 220, 240
46–54	60	50	80, 100, 120, 140, 160, 180, 200, 220, 240
55–63	75	30	80, 100, 120, 140, 160, 180, 200, 220, 240
64–72	75	40	80, 100, 120, 140, 160, 180, 200, 220, 240
73–81	75	50	80, 100, 120, 140, 160, 180, 200, 220, 240
82–90	90	30	80, 100, 120, 140, 160, 180, 200, 220, 240
91–99	90	40	80, 100, 120, 140, 160, 180, 200, 220, 240
100–108	90	50	80, 100, 120, 140, 160, 180, 200, 220, 240

generated near drillpipe surface with drillpipe rotation. The cuttings are tangentially dragged by viscosity force of drilling fluid, which can improve hole cleaning. However, due to the reduction of tangential velocity of drilling fluid, the drag force acting on cuttings gradually becomes less and some cuttings can not be effectively transported into main flow field. As a result, these cuttings will settle at the bottom of annulus and eventually cuttings bed is formed. This indicates high rotation speed can provide more energy for suspending the cuttings, makes most cuttings fully suspended, and decrease cuttings bed height.

Distribution of annular cuttings with pipe rotation

The simulations on the distribution of cuttings in annulus for angle at 45° and 60° were conducted, and the following conclusions can be reached by comparing Fig. 4 with 5:

- Cuttings present asymmetrical distribution on either side of drillpipe, and cuttings bed is easy to be formed when low mud flow rate is used.
- As drillpipe rotation speed increases, cuttings concentration in annulus decreases for any pipe rotation speed, but the level of enhancement is more pronounced with the decrease at flow rate.

**Fig. 3** Tangential velocity profile in an eccentric annulus with pipe rotation**Fig. 4** Annular cuttings concentration contour at the angle of 45°

- Lower cuttings concentration near drillpipe are presented, which indicates that drilling fluid can obtain high tangential velocity under the drillpipe rotation, and cuttings are suspended by high drag force and transported by axial fluid flow.
- In the low flow rate, cuttings are more transported at the angle of 60° than 45°, but inclination shows only a minor effect on cuttings concentration in high flow rate and rotation speed.
- Pure drilling fluid region, dispersed layer, and stationary cuttings bed are emerged in low rotary speed or flow rate. As the flow rate is increased, the intensity of turbulent eddies grows in strength and eventually the particles of the cuttings bed are totally lift into the dispersed layer and there only exists pure drilling fluid layer and dispersed layer. Finally, with further

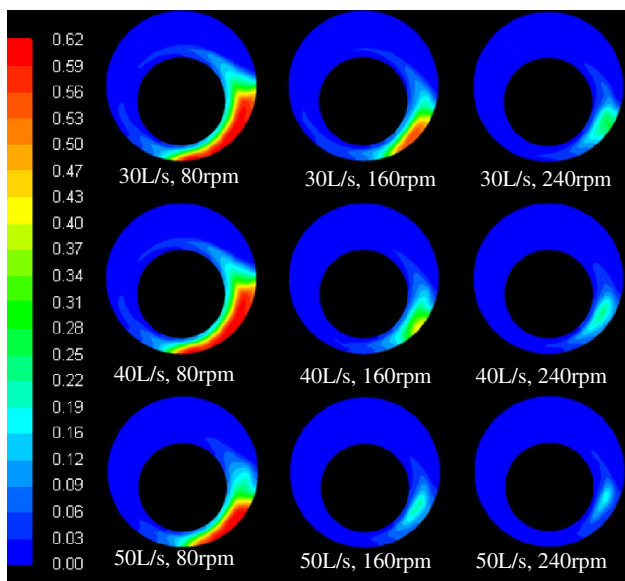


Fig. 5 Annular cuttings concentration contour at the angle of 60°

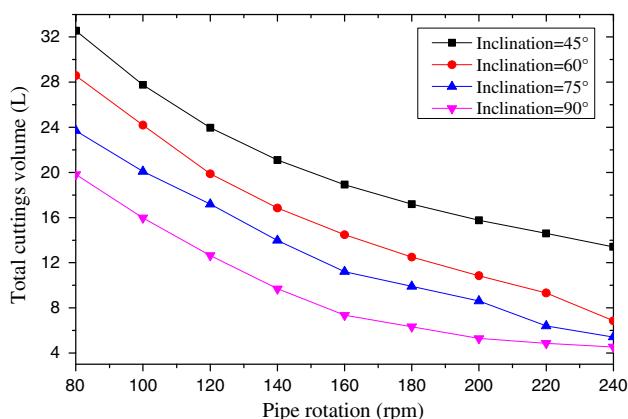


Fig. 6 Effect of pipe rotation on cuttings volume for different inclinations and flow rate 30 L/s

increases in the flow rate, all particles will be transported in a heterogeneous flow.

Effects of pipe rotation on cuttings concentration and pressure drop

As seen from Figs. 6, 7, 8, 9, at fluid rates from 30 to 50 L/s and inclinations horizontal to 60°, pipe rotation can significantly decrease the total volume of annular cuttings. Even though this is the case, still a decrease in the cuttings volume is observed with the increase of rotation speed. However, the additional contribution of drillpipe rotation on decreasing cuttings volume is almost negligible after a certain rotation speed when flow rate reaches 50 L/s or inclination is close to horizontal. Considering the limited rotation speed in real drilling, pipe rotation has a significant

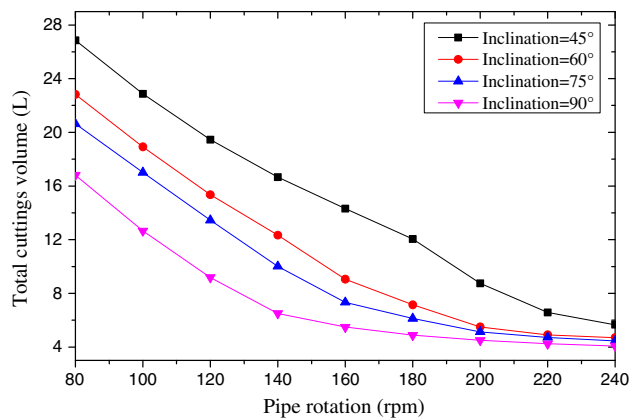


Fig. 7 Effect of pipe rotation on cuttings volume for different inclinations and flow rate 40 L/s

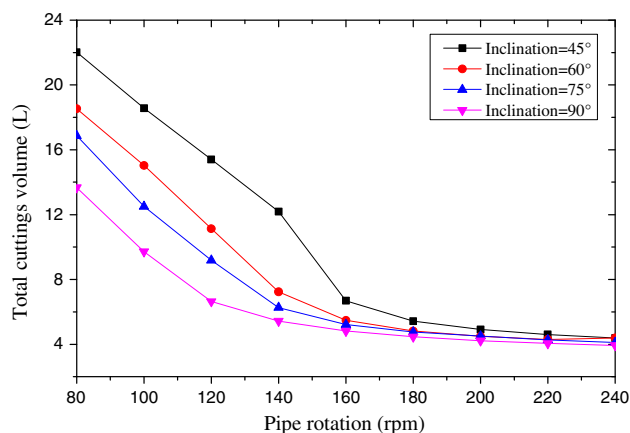


Fig. 8 Effect of pipe rotation on cuttings volume for different inclinations and flow rate 50 L/s

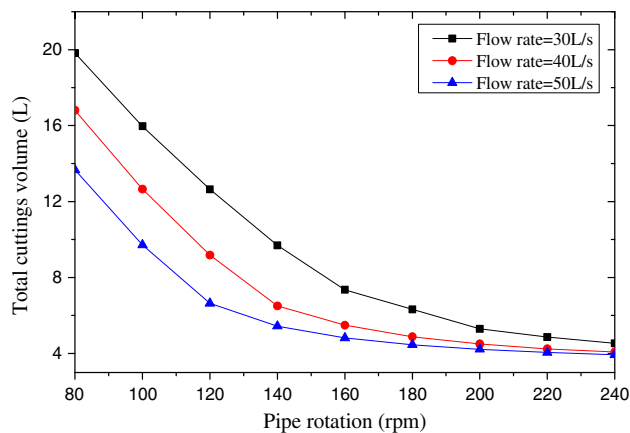


Fig. 9 Effect of pipe rotation on cuttings volume for different flow rates in horizontal wellbores

impact on hole cleaning in low flow rates. In addition, the pipe rotation effect on hole cleaning is also affected by inclination. In particular, in the lower pipe rotation speeds, the cuttings volume in the annulus is more for lower

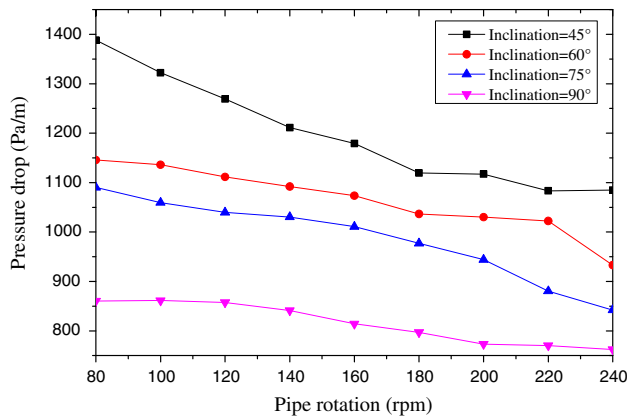


Fig. 10 Effect of pipe rotation on annular pressure drop for different inclinations and flow rate 30 L/s

inclinations than for higher inclinations, which means that cuttings bed is easier to be formed in the low inclination. This conclusion is consistent with Li et al.'s (2001) observation that the toughest section for hole cleaning is the build section rather than the vertical or the horizontal section.

As shown from Figs. 10, 11, 12, the influences of drillpipe rotation for different flow rates and inclinations on annular pressure drop are depicted. For any flow rate and inclination, as the pipe rotation speed is increased, annular pressure drop is decreased. The pressure drop almost reduces by half when pipe rotation increases from 80 to 160 rpm with 50 L/s flow rate at 45°. But when keeping flow rate 50 L/s, the pressure drop almost remains constant after pipe rotation speed reaches 180 rpm. Also, in the low rotation speed, producing pressure drop becomes more at the lower angle than at higher angle.

Empirical correlations

It is considered that the ratio of cuttings volume and wellbore volume is function of inclination, flow rate, density and size of cuttings, viscosity and density of drilling fluid, annular hydraulic diameter, pipe rotation, and gravity. Major parameters affecting cuttings concentration can be defined as:

$$\frac{V_b}{V_w} = f(\theta, v, \omega, \rho_l, \rho_s, \mu, D_h, g, d_c) \tag{5}$$

Based on Buckingham- π theorem, seven dimensionless groups are determined as follows (Ozbayoglu et al. 2008):

$$\pi_1 = \frac{\rho_l v D_h}{\mu} \tag{6}$$

$$\pi_2 = \frac{v^2}{g D_h} \tag{7}$$

$$\pi_3 = C \tag{8}$$

$$\pi_4 = \theta \tag{9}$$

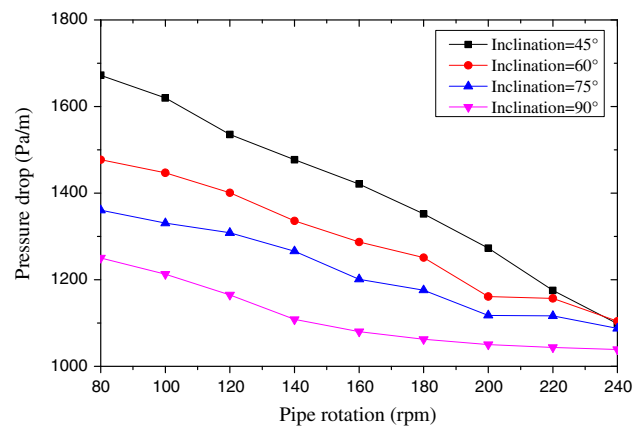


Fig. 11 Effect of pipe rotation on annular pressure drop for different inclinations and flow rate 40 L/s

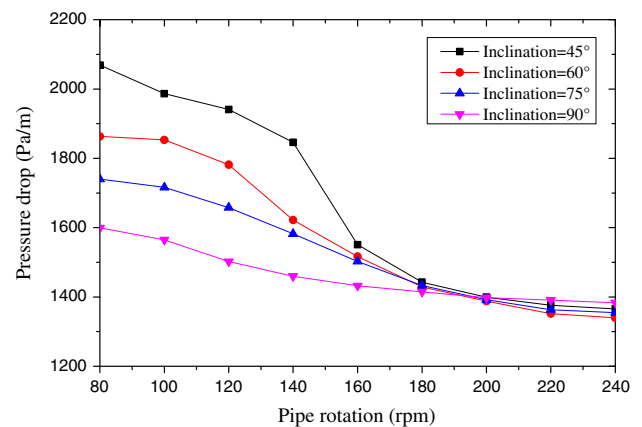


Fig. 12 Effect of pipe rotation on annular pressure drop for different inclinations and flow rate 50 L/s

$$\pi_5 = \frac{d_c}{D_h} \tag{10}$$

$$\pi_6 = \frac{\rho_l v d_c}{\mu} \tag{11}$$

$$\pi_7 = \frac{\omega D_h}{v} \tag{12}$$

where V_b represents cuttings volume (m^3), V_w is wellbore volume (m^3), θ is the inclination ($^\circ$), v represents fluid flow rate m/s, ω stands for pipe rotation (s^{-1}), ρ_l is the density of drilling fluid (kg/m^3), ρ_s is the density of cuttings (kg/m^3), μ represents the viscosity of drilling fluid (Pa s), d_c is the cuttings size (m), D_h stands for the hydraulic diameter (m), C is the cuttings concentration, g stands for the gravity (N/kg).

In this simulation, size and density of cuttings, injected cuttings concentration, viscosity and density of drilling fluid are constant, therefore, π_3 , π_5 , and π_6 can be negligible, and Eq. (5) is rewritten by:

$$\frac{V_b}{V_w} = a_0 \pi_1^{a_1} \pi_2^{a_2} \pi_4^{a_3} \pi_7^{a_4} \quad (13)$$

Considering the effect of cuttings concentration, annular pressure drop can be defined as:

$$\frac{\Delta p}{\Delta L} = a_0 \pi_1^{a_1} \pi_2^{a_2} \pi_4^{a_3} \pi_7^{a_4} \left(\frac{V_b}{V_w}\right)^{a_5} \quad (14)$$

The least square method is applied to linearly regress for 12 groups data, and cuttings concentration and annular pressure drop for inclinations from 45° to 90° can be determined, respectively:

$$\frac{V_b}{V_w} = 0.01 \left(\frac{\rho_l v D_h}{1,000\mu}\right)^{6.0493} \left(\frac{v^2}{g D_h}\right)^{-4.3133} \times (0.1\theta)^{-0.8977} \left(\frac{10\omega D_h}{v}\right)^{-1.3677} \quad (15)$$

$$\frac{\Delta p}{\Delta L} = 100 \left(\frac{\rho_l v D_h}{1,000\mu}\right)^{1.0547} \left(\frac{v^2}{g D_h}\right)^{0.1376} (0.1\theta)^{-0.0740} \times \left(\frac{10\omega D_h}{v}\right)^{0.1435} \left(\frac{100V_b}{V_w}\right)^{0.2877} \quad (16)$$

Conclusions

In this study, CFD simulations of the effects of drillpipe rotation on cuttings transport behavior in the complex structure well were performed using an Euler multiphase model. The following conclusions can be drawn as follows:

- Pipe rotation has an important effect on distribution of annular cuttings in inclined section and causes the asymmetrical distribution of cuttings along the circumference direction.
- Pipe rotation can significantly increase the tangential velocity of drilling fluid, which generates the drag force along the tangential direction, and the force can restrain cuttings bed development to some extent. In high rotation speeds, dragged effect is more pronounced, and the fully suspended flow is easy to be developed.
- At low or medium flow rates, increasing pipe rotation speed can significantly reduce cuttings volume and annular pressure drop. However, there exists a threshold point at high flow rates, after which no matter how much the pipe rotation speed is increased, the magnitudes of cuttings volume and annular pressure drop almost remain constant.
- Buckingham- π theorem was applied to define dimensionless groups, and eventually, user friendly empirical correlations about the cuttings concentration and pressure drop were developed using least square

method based on the CFD simulations on cuttings transport.

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