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Simulation of cuttings transport with foam in deviated wellbores using computational fluid dynamics

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Abstract Foam is non-Newtonian pseudo-plastic fluid, which is used for drilling, well intervention, and stimulation. Predicting the cutting transport efficiency of foam in the wellbore annulus is very important to optimize the drilling process. In this paper, the cuttings transport process with foam is numerically simulated using an Eulerian two-phase model in inclined wellbores. A computational fluid dynamics (CFD) software package called FLUENT was used for this goal. The effect of foam quality, foam velocity, drill pipe rotation, and wellbore inclination on cuttings transport phenomena in both concentric and eccentric annulus was investigated. The simulation results are compared to the experimental data from previous studies, with a relative error less than 8 %. This study shows the reliability of the CFD simulation in replicating the actual physical process.

Keywords Cuttings transport · CFD simulation · Foam drilling · Deviated wellbores

Introduction

Foam is often used for underbalanced drilling. Foam fluids generally consist of 5–25 % of the liquid phase and 75–95 % of the gaseous phase. The liquid phase could be fresh water or brines. The gaseous phase is usually an inert gas. A surfactant is used as a stabilizer and it comprises about 5 % of the liquid phase. The liquid phase can be weighted up using heavy brines or barites. The advantages of foam drilling over conventional mud drilling include high penetration rates, a high cuttings transport ratio, and less formation damage. For the drilling with low bottom-hole pressures, the use of a lighter fluid, such as foam, is required (Zhu et al. 1995; Teichrob and Manuel 1997; Foster and Steiner 2007; Ramalho 2006; Chen 2005; Wang et al. 2009b). In drilling operation, the fluid is pumped through the drill pipe down to the hole. Then the fluid with cuttings is circulated back up to the surface through the annular space between the drill pipe and the hole. Cuttings transport as a multiphase flow, is important to successful drilling operation, which can affect the operation cost, the time, and the quality of well drilling and completion. Inadequate hole cleaning can result in many costly problems, such as pipe stuck, lost circulation, premature bit wear, slow penetration rate, poor cement jobs, formation fracturing, high torque and high drag. Cuttings transport is controlled by many variables, such as the well deviation angle, hole diameter, drill pipe diameter, drill pipe rotation, drill pipe eccentricity, rate of penetration (ROP), cuttings characteristics (including the size, shape and porosity of bed), fluid velocity, fluid type, and the complex non-Newtonian fluid rheology. A comprehensive review of the cuttings transport was given by Nazari et al. (2010). Much research has been carried out on cuttings transport with conventional drilling fluids in horizontal and directional wells. In addition, some empirical and mechanistic models have been developed for cuttings transport (Clark and Bickham 1994; Larsen et al. 1997; Nguyen and Rahman 1998; Kelessidis and Bandelis 2004; Loureiro et al. 2010; Piroozian et al. 2012). Foam as a non-Newtonian pseudo-plastic fluid has high viscosity. Its viscosity is greater than either its liquid or gaseous components. Its density is usually less than one-half that of water. Therefore, foam could

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promote efficient cuttings transport. Its low density allows for underbalanced conditions, an increased ROP, and minimal formation damage. Foams are also stable at high temperatures and pressures (Ozbayoglu 2002; Ozbayoglu et al. 2005; Chen 2005; Duan 2007).The rheological properties and hydraulic of foam have been studied much less than conventional (incompressible) drilling fluids. Even less is known about the cuttings transport capabilities of foam. Determining how to effectively remove cuttings with foam is critical to the drilling process. The cuttings particles with the foam drilling fluid could create problems similar to those with conventional drilling fluid. The solids particles can also change foam properties, which may completely alter the plan for controlling down-hole pressure. The majority of research related to cuttings transport with foam describes operators' experiences, field practices, and one-dimensional numerical simulations of the cuttings transport process (Machado and Ikoku 1982; Owayed 1997; Saintpere et al. 2000; Martins et al. 2001; Ozbayoglu 2002; Ahmed et al. 2003; Li and Kuru 2003; Chen 2005; Capo et al. 2006; Chen et al. 2007; Osunde and Kuru 2008; Wang et al. 2009b; Duan 2007; Duan et al. 2010; Gumati and Takahshi 2011).

CFD modeling provides an alternative way to investigate fluid flow in complex geometries. It complements experimental work with less cost. Also, a CFD-based approach can evaluate complex flow problems in a way that is impossible to do, experimentally. Specifically, three-dimensional (3D) solid–liquid two-phase flow problems under a wide range of flow conditions and sediment characteristics can be evaluated. CFD has rarely been applied in conventional drilling operations and cutting transport phenomena (Bilgesu et al. 2007; Pereira et al. 2010; Wang et al. 2009a; Han et al. 2010; Al-Kayiem et al. 2010; Zhonghou et al. 2011; Hajidavalloo et al. 2013). A literature review indicated that there are not many 3D CFD simulation studies of foam cutting transport, especially involving inclined wellbores with pipe rotation and eccentricity. In this study, cuttings transport with foam was simulated in a 3D concentric and eccentric annular section, using FLUENT software. The simulation results were compared with the experimental results based on the previous studies (Chen 2005; Chen et al. 2007; Duan 2007; Duan et al. 2010). We believe the results of this study to be useful in explaining the effect of various operational drilling parameters on cuttings transport with foam in deviated and horizontal wellbores without conducting experimental studies.

Foam properties

Foam is a mixture of liquid, surfactant and other chemical additives, and compressed gasses. The gaseous phase could be nitrogen, carbon dioxide, natural gas or air. Foam is a multiphase, metastable, compressible, non-Newtonian fluid, and has a consistency similar to that of shaving cream. Foam properties are briefly discussed in the following section (Zhu et al. 1995; Rojas et al. 2002; Li and Kuru 2005).

Foam quality

Foams are generally characterized by their quality (Γ), which is the ratio of the gas volume to the total foam volume:

$$\Gamma = \frac{V_{\mathrm{g}}}{V_{\mathrm{g}} + V_{\mathrm{l}}} \times 100 \tag{1}$$

where Γ is the foam quality (%), V_{g} is the gas volume, and V_{l} is the liquid volume. The foam quality (Γ) ranges between 0 and 1, depending on the amount of gas in the foam. An increase in the gas component, by increasing the gas flow rate, increases foam quality, which in turn increases the effective viscosity of the foam and decreases the density of the foam. An increase in the liquid component, by increasing the liquid injection rates, reduces the foam quality but increases the bottom-hole pressure. The presence of a gas component in foam also makes its quality to change with temperature and pressure.

Foam density

The change in the volume of the gas phase with the change in temperature and pressure will result in a change in the density of the foam. For the foam flow, it is assumed that the liquid volume does not change with temperature and pressure. For a particular pressure and temperature condition, foam is treated as a homogenous fluid and the density can be expressed as follows:

$$\rho_{\mathrm{f}} = \Gamma \rho_{\mathrm{g}} + (1 - \Gamma)\rho_{\mathrm{l}} \tag{2}$$

where ρ_{f} is the foam density, ρ_{g} represents the gas density and ρ_{l} denotes the liquid density.

Foam rheology

The rheological behavior of foams plays a fundamental role in determining the efficiency of cuttings transport in drilling operations. Considerable effort has been made by a few of the investigators to study the rheology of foams (Krug and Mitchell 1972; Sanghani and Ikoku 1983; Herzhaft 1999; Shah et al. 2010; Gajbhiye and Kam 2012). However, there are some disagreements among researchers in selecting the best model to describe the flow behavior of foam, because of differing analytical approaches, experimental setups, gas phases, and types of foaming agent and other additives. Studies have shown that foams can be

treated as pseudo-plastic power law fluids (Sanghani and Ikoku 1983; Enzendorfer et al. 1995), as Bingham plastic fluids (Mitchell 1969; Beyer et al. 1972; Blauer et al. 1974) and even as Herschel–Bulkley (HB) fluids (Bonilla and Shah 2000; Saintpere et al. 2000; Sani and Shah 2001; Ahmed et al. 2009). Such models can be expressed mathematically as:

Bingham plastic:

$$\begin{cases} \gamma = 0 & |\tau| < \tau_y \\ \tau = \tau_y + \mu_p \gamma & |\tau| > \tau_y \end{cases} \quad (3)$$

Power law:

$$\tau = K\gamma^n \quad (4)$$

Herschel–Bulkley:

$$\begin{cases} \gamma = 0 & |\tau| < \tau_y \\ |\tau| = \tau_y + K|\gamma|^n & |\tau| > \tau_y \end{cases} \quad (5)$$

where τ and τ_y are the shear stress and yield stress (Pa), respectively; μ_p, K and n are the fluid plastic viscosity (Pa s), consistency (Pa s^n), and fluid behavior indices, respectively, while γ denotes the shear rate (1/s).

Mathematical model of Euler multiphase flow

In the present study, Euler-multiphase flow approach was used for the liquid–solid flow analysis (cuttings transport process). The conservation of mass and momentum equations were solved by specifying appropriate boundary and initial conditions. The governing equations of multiphase flows are briefly discussed as follows (FLUENT 2006; Yeoh and Tu 2010).

The volume fraction is defined as:

$$V_q = \int_V \alpha_q \, \mathrm{d}V \quad (6)$$

where

$$\sum_{q=1}^n \alpha_q = 1 \quad (7)$$

where V is the volume (m^3), α denotes volume fraction (%), q represents sequence ($q = 1, 2, \ldots, n$), and n stands for total phase number.

The mass conservation equation for phase q is:

$$\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \overrightarrow{v}_q) = \sum_{p=1}^n \dot{m}_{pq} + S_q \quad (8)$$

where ∇ is the divergence, ρ denotes density (kg/m^3), v represents velocity vector (m/s), t is the motion time (s), S_q stands for source term (here $S_q = 0$) and $\dot{m}_{pq}$ is mass

transfer between phases p and q. In reality there is no mass transfer between solid and liquid phases, hence $\dot{m}_{pq} = 0$.

The momentum conservation equation for the liquid phase q is given by:

$$\begin{aligned} &\frac{\partial}{\partial t}(\alpha_q \rho_q \overrightarrow{v}_q) + \nabla \cdot (\alpha_q \rho_q \overrightarrow{v}_q \overrightarrow{v}_q) \\ &= -\alpha_q \nabla P + \nabla \cdot \overline{\overline{\tau}}_q + \alpha_q \rho_q \overrightarrow{g} \\ &\quad + \sum_{p=1}^n (K_{pq}(\overrightarrow{v}_p - \overrightarrow{v}_q) + \dot{m}_{pq} \overrightarrow{v}_{pq} - \dot{m}_{qp} \overrightarrow{v}_{qp}) \\ &\quad + (\overrightarrow{F}_q + \overrightarrow{F}_{\mathrm{lift},q} + \overrightarrow{F}_{\mathrm{Vm},q}) \end{aligned} \quad (9)$$

where F_q is an external body force (N) $F_{\mathrm{lift};q}$ denotes a lift force of q phase (N), $F_{\mathrm{Vm},q}$ represents a virtual mass force (N), K_{pq} is the interphase momentum exchange coefficient, P refers to the pressure shared by all phases (Pa), and $\overline{\overline{\tau}}_q$ is the qth stress–strain tensor (Pa) given by:

$$\overline{\overline{\tau}}_q = \alpha_q \mu_q (\nabla \overrightarrow{v}_q + \nabla \overrightarrow{v}_q^T) + \alpha_q \left(\lambda_q - \frac{2}{3}\mu_q\right) \nabla \cdot \overrightarrow{v}_q \overline{\overline{I}} \quad (10)$$

where λ_q and μ_q are the shear and bulk viscosity of phase q (Pa s).

Momentum conservation equation for the solid:

$$\begin{aligned} &\frac{\partial}{\partial t}(\alpha_s \rho_s \overrightarrow{v}_s) + \nabla \cdot (\alpha_s \rho_s \overrightarrow{v}_s \overrightarrow{v}_s) \\ &= -\alpha_s \nabla P - \nabla P_s + \nabla \cdot \overline{\overline{\tau}}_s + \alpha_s \rho_s \overrightarrow{g} \\ &\quad + \sum_{p=1}^n (K_{ls}(\overrightarrow{v}_1 - \overrightarrow{v}_s) + \dot{m}_{ls} \overrightarrow{v}_{ls} - \dot{m}_{sl} \overrightarrow{v}_{sl}) \\ &\quad + (\overrightarrow{F}_s + \overrightarrow{F}_{\mathrm{lift},s} + \overrightarrow{F}_{\mathrm{VM},s}) \end{aligned} \quad (11)$$

where P_s is the solid pressure (composed of a kinetic term and a term for particle collisions), $K_{ls} = K_{sl}$ is the momentum exchange coefficient between fluid and solid phase (shown as l and s, respectively), and n is the total number of phases.

In this study, the set of governing partial differential equations was discretized and solved using FLUENT software as a finite volume technique, based on granular multiphase flows.

Geometric domain, grid setup and flow conditions

The physical domain can be a concentric or eccentric annulus. The annulus between the drill pipe and the borehole or casing has been represented as a concentric annulus (Chen et al. 2007) and as an eccentric annulus (Duan et al. 2010) with eccentricity ($e = E/(R_o - R_i)$) of 0.78, where E is offset distance between the

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centers of the inner tube, R_i, and the outer tube, R_o, of annulus.

The inner diameter of the casing is 146.3 mm (5.76 in) and the drill pipe outer diameter is 88.95 mm (3.5 in). The length of the annulus is 22.25 m (73.00 ft). The geometry domain was gridded to simulate the mathematical model. The geometry and computational grid of the concentric and eccentric annulus are shown in Fig. 1.

The cuttings have a mean diameter of 3 mm, a density of 2,610 kg/m^3, and a porosity of 38 %. The cuttings injection rate was 15 lb/min (6.8 kg/min) corresponding to the *ROP* of 50 ft/h (15 m/h) for the 5.76″ hole size. Therefore, for a fixed *ROP* the cutting velocity at the inlet of the geometric domain is calculated by the mass balance equation (Larsen et al. 1997):

$$V_{cut} = \frac{ROP}{3,600\left(1 - \frac{D_{pipe}}{D_{hole}}\right)^2 cc}(1 - \phi) \qquad (12)$$

where V_{cut} is the cuttings velocity (ft/s) in input; *ROP* denotes the rate of penetration (ft/h); ϕ represents the cutting porosity (as a decimal); D_{pipe} is the pipe diameter (in); D_{hole} stands for the hole diameter (in); and cc is the input cutting concentration (as a decimal).

The cuttings transport ratio (Sifferman et al. 1974) was used to evaluate the cutting transport efficiency:

$$R_T = \frac{V_t}{V_a} \qquad (13)$$

where R_T is the cuttings transport ratio, V_t is the average cuttings transport velocity and V_a is the average fluid annular velocity in annulus. The cuttings transport ratio also can be expressed in terms of the cuttings concentration (c) in the annulus as follows:

$$R_T = 1 - c \qquad (14)$$

The cuttings concentration (c) in an annulus is defined as:
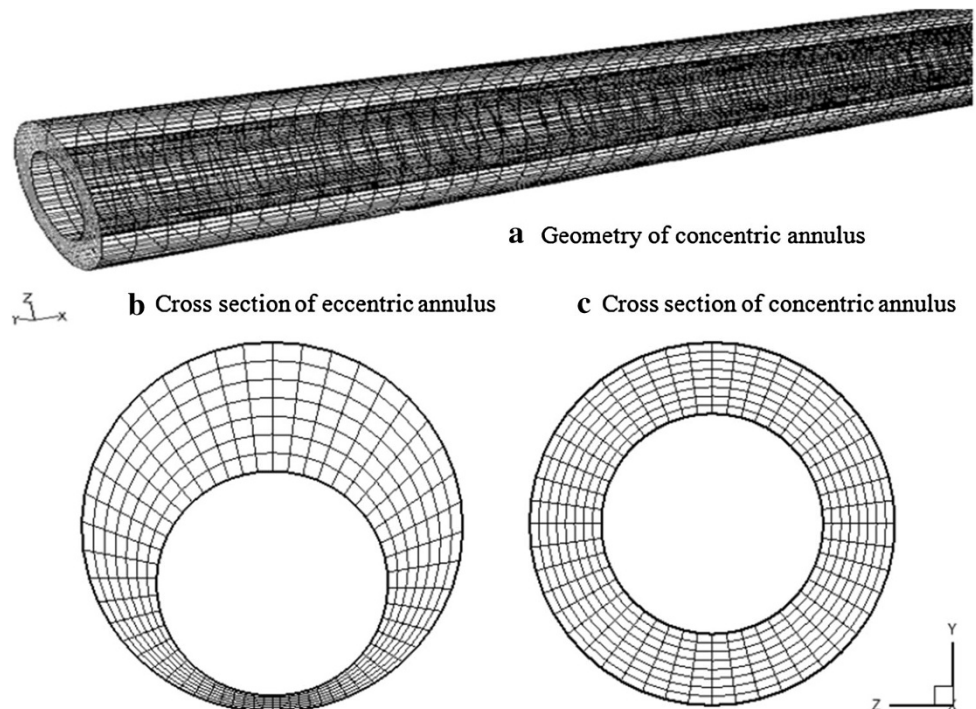
$$c = \frac{\text{Net volume occupied by cuttings}}{\text{Total annulus volume}} \qquad (15)$$

A higher cuttings transport ratio means there is a relatively lower cuttings concentration in the wellbore.

Both the HB and Power Law (PL) models can be used to describe the rheological property of the foam. The rheological parameters of these two models can be estimated using the genetic algorithm (GA) method based on earlier work (Rooki et al. 2012). In Fig. 2 the PL model is compared with the experimental shear stress/shear rate data (Duan 2007).

The rheological parameters, the correlation coefficient (R) and the sum square error (SSE) of the curve fitting for PL and HB models are listed in Table 1. The table shows that the values of the linear regression coefficient (R) are greater than 0.99. This indicates that the correlation was

Fig. 1 Geometry domain and the computational grid

a Geometry of concentric annulus

b Cross section of eccentric annulus

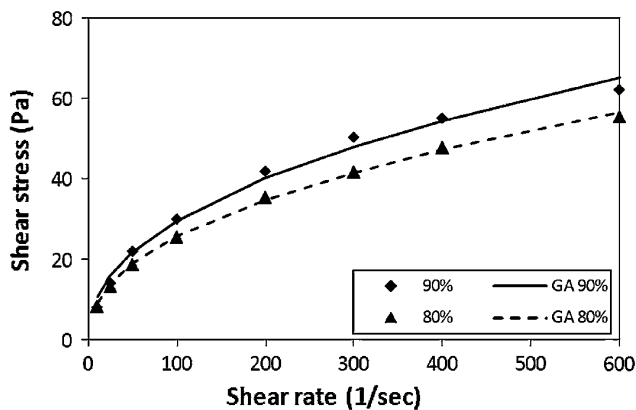**c** Cross section of concentric annulus

Fig. 2 Comparison between the foam generator viscometer data versus the PL model at 100 psi

excellent and the models accurately describe the rheological behavior of the foam systems under investigation. The PL model has a lower SSE when compared with the HB model. Therefore, the PL model was considered for the CFD simulation in this study.

Results and discussion

The CFD simulation was used to simulate 3D flow of solid–liquid mixtures in both concentric and eccentric annuli, which represents the drilling operation with the non-Newtonian foam fluid. The foam is treated as a Power law non-Newtonian isothermal fluid (Table 1). The simulations were conducted to investigate the effect of foam qualities, foam velocity, drill pipe rotation and hole deviation on the cuttings transport ratio. The flow regime in this study is considered as laminar flow. Table 2 summarizes the detail of the simulation input information which is based on the experimental studies from Duan (2007) and Chen (2005).

Effect of foam quality and drill pipe rotation

To validate CFD simulation, the numerical results of the cuttings transport ratio were compared with the experimental results for both concentric annulus (Chen 2005;

Chen et al. 2007) and eccentric annulus with pipe rotation (Duan 2007; Duan et al. 2010). Figure 3 compares the experimental (Chen 2005; Chen et al. 2007) cuttings transport ratio ($R_T = 1 - c$) with the CFD results in a horizontal concentric annulus with different foam qualities. Figure 4 compares the experimental (Duan 2007; Duan et al. 2010) cuttings transport ratio with the CFD results for the horizontal eccentric annulus with different rotation speed. Both figures show agreement between the CFD simulation and the experimental data with the relative error less than 8 %.

With a higher foam velocity in the axial direction of the annulus, the drag force exerted on the solid particles increases and it results in a higher cuttings transport ratio. The fluid velocity has the largest effect on the cuttings transport. For 80 % foam quality, the cuttings transport ratio increased to about 9.5 % when foam velocity increased from 2 to 5 ft/s in concentric annulus.

Also the foam with a higher foam quality (a higher k value and a lower n value) has a flatter annular velocity profile. The flatter velocity profile means that there is a higher chance of the cuttings near solid wall surfaces being exposed to the high annular velocity, and that there is a lower chance of cuttings settling at the lower side of the wellbore. Therefore, a higher foam quality increases the cuttings lifting capacity of the foam. This indicates that the foam fluid can significantly enhance the drag force and the lift force on cutting particles, especially for a low foam velocity. As foam quality increased from 80 to 90 %, the cuttings transport increased from 0.718 to 0.75 for a constant velocity of 2 ft/s in concentric annulus. Figure 5 shows the effect of foam quality on the cuttings distribution in the annulus using PL rheological model. Higher foam quality has a lower density, so an increase in foam quality reduces the buoyancy force, and the maximum packing of cuttings increases in the annulus. However, the higher quality foam has a higher cuttings transport ratio, because its viscosity is greater than the low quality foam. It can be also concluded from Fig. 5 that in the eccentric annulus, the cuttings accumulation increases in the narrow gap of the annulus near the bottom of the wellbore and the maximum packing of cuttings in annulus increases with respect to concentric annulus.

Table 1 The HB and PL rheological parameters for aqueous foam systems (at 100 psi and 80°F conditions)

Model	Foam quality (%)	τ_0 (Pa)	K (Pa s^n)	n (–)	SSE (Pa^2)	R
HB model	90	2.250	3.137	0.469	43.426	0.995
PL model	90	0	3.920	0.438	33.14	0.995
HB model	80	2.200	2.594	0.476	5.778	0.999
PL model	80	0	3.385	0.439	2.661	0.999

Table 2 Simulation input information of cuttings transport using aqueous foam

parameter	Value
Annular size	5.76″ by 3.5″
Pipe rotation (rpm)	0, 80, 120
Foam velocity (ft/s)	2, 3, 4, 5
Foam quality (%)	80, 90
Eccentricity (–)	0, 0.78
Temperature (F)	80
Pressure (psi)	100
Cuttings size (mm)	3
Cuttings density (kg/m^3)	2610
Hole inclination (°)	0, 15, 30, 45, 75, 90
ROP (ft/h)	50
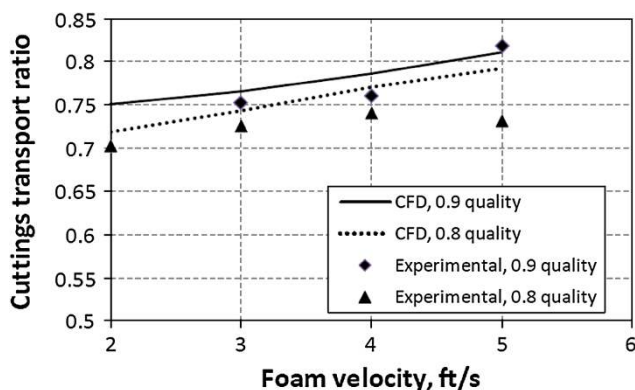
Fig. 3 Comparison of the experimental (Chen 2005; Chen et al. 2007) cuttings transport ratio and CFD simulation results in a horizontal concentric annulus, no pipe rotation
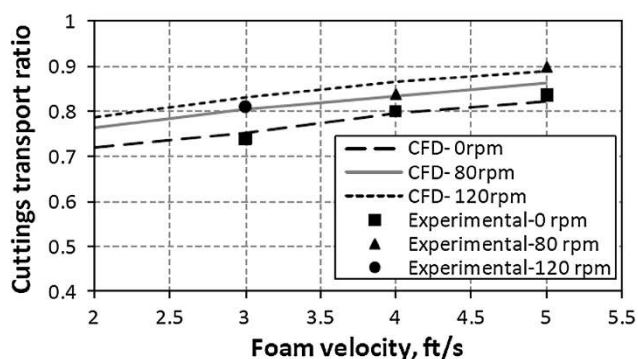
Fig. 4 Comparison of the experimental (Duan et al. 2010) cuttings transport ratio and CFD simulation results in a horizontal eccentric annulus at 100 psi (90 % foam quality)

Pipe rotation influences the cuttings bed erosion significantly. Simulation results indicate that the pipe rotation results in a velocity profile that makes the bed erosion easier. Optimizing pipe rotation can also increase drilling

efficiency. The effect of pipe rotation on cuttings transport in horizontal eccentric and concentric annuli is shown in Figs. 4 and 6, respectively. As shown in these figures, the cuttings transport ratio increases with increasing pipe rotation. For 90 % foam quality, the cuttings transport ratio increased from 0.72 to 0.79 as the pipe rotation increased from 0 to 120 rpm for a foam velocity of 2 ft/s in eccentric annulus. Pipe rotation not only reduces the cuttings concentration in the annulus but also leads to a reduction of the frictional pressure loss. A reduction of the pressure gradient (Fig. 7) is caused by an increased shear rate and a decreased cuttings concentration, both due to the pipe rotation. Near the surface of the rotated drill pipe, the local effective viscosity reduction is induced for the foam as a pseudo-plastic fluid. This decreased local viscosity reduces the friction near the drill pipe wall, acting as a lubricant. Therefore, it results in the decreased pressure gradient.

Figure 8 shows the effect of the pipe rotation on the cuttings distribution in both concentric and eccentric horizontal annuli. In the case with no pipe rotation, the profile of cuttings volume fraction is symmetric around the pipe's axis, and the most of cuttings are at the bottom of the annulus because of the gravitation. In the case with the pipe rotation, the rotation prevents the formation of cuttings beds and lifts the cuttings upward. The pipe rotation also decreases the cuttings concentration in the annulus and minimizes bit sticking.

Figure 9 shows the effect of pipe rotation on the cuttings velocity in both concentric and eccentric horizontal annulus. For the eccentric case, the pipe rotation generates rotational flow near the bottom of the wellbore. It results in a smaller area with a low axial velocity (the velocity in the x direction) for the rotated pipe case when compared with the non-rotating pipe case. As a result, pipe rotation decreases the accumulation of particles near the bottom of the wellbore. However, in the concentric annulus, this effect is not significant, especially for a high fluid velocity.

Effect of hole inclination

Figure 10 shows the effect of the wellbore deviation angle on the cuttings transport ratio. For high deviation angles (60°–90°), a stationary cuttings bed can be formed, and cuttings are transported by a sliding and rolling mechanism. For intermediate angles (30°–60°), a churning, moving cuttings bed can be formed, and the cuttings are transported by a lifting mechanism. At near-vertical angles (0°–30°), particle settling controls the cuttings transport. The cuttings transport ratio decreases with an increasing well deviation angle for a given foam flow rate. The gravity effect in horizontal angle is perpendicular to the flow direction. The cuttings transport ratio in the near-vertical well is not very sensitive to foam

Fig. 5 Effect of foam quality on the cuttings distribution in the concentric and eccentric horizontal annulus (no pipe rotation, fluid velocity = 5 ft/s)
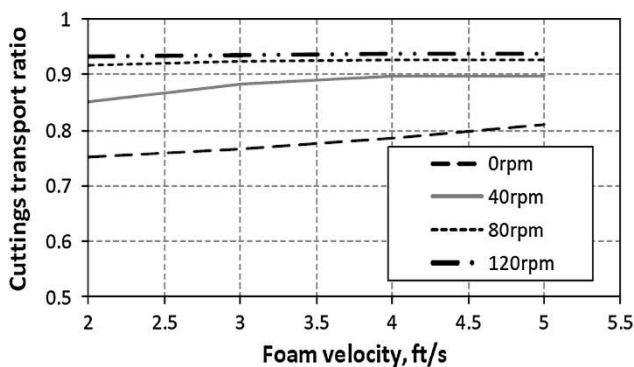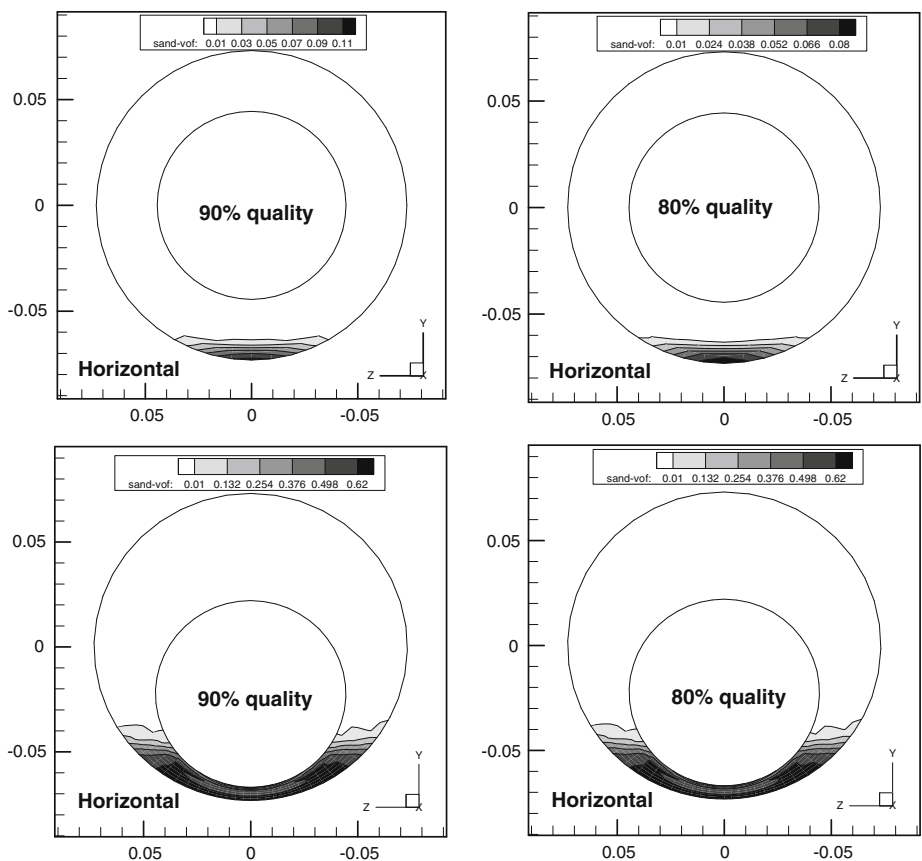

Fig. 6 Effect of pipe rotation on the cuttings transport ratio in a horizontal concentric annulus (90 % quality foam, 100 psi)
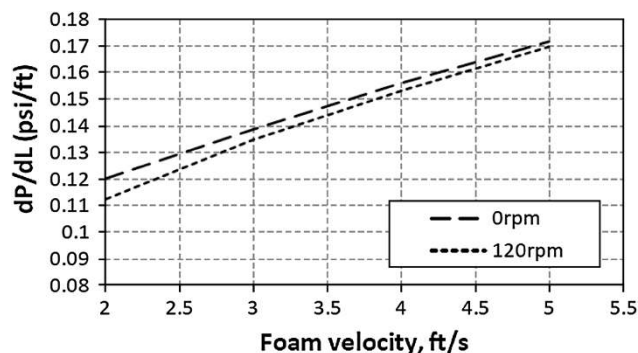

Fig. 7 Effect of pipe rotation on the pressure loses in a horizontal concentric annulus

velocity due to the good suspension capability of the foam. For these reasons, foam has an excellent capacity for cuttings transport, especially for low velocities in near-vertical wellbores. The cuttings transport ratio decreases with the increase of the deviation angle from 0° to 45°, and it remains constant or varies slightly between 45° and 90°.

Figure 11 shows the effect of the deviation angle on the distribution of the cuttings volume fraction in the concentric annulus under the non-rotating condition. This figure shows that the cutting distribution only in the vertical annulus is uniform. For deviated and horizontal wellbore, the cuttings intend to accumulate near the bottom of the wellbore due to the gravitation effect.

Conclusions

In this study, the curve fitting with the generic algorithm for the foam viscometer data showed that the PL model is the better rheological model to describe the foam rheological property.

Fig. 8 Effect of pipe rotation on the cuttings concentration distribution in both concentric and eccentric horizontal annulus (fluid velocity = 5 ft/s, foam quality = 90 %)
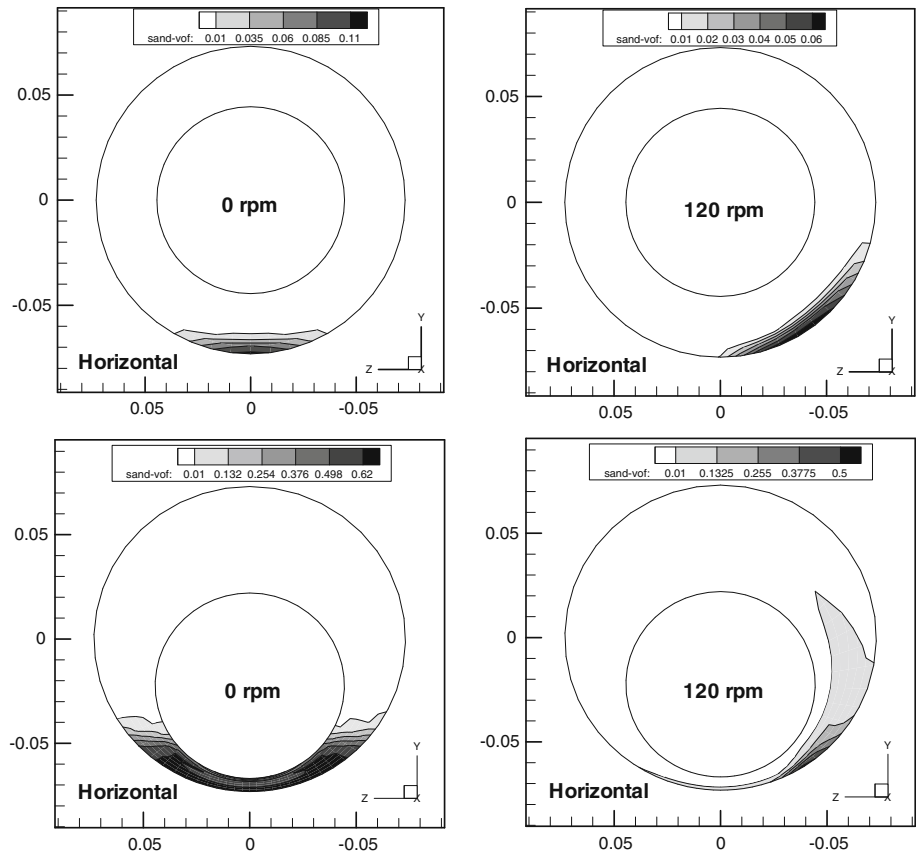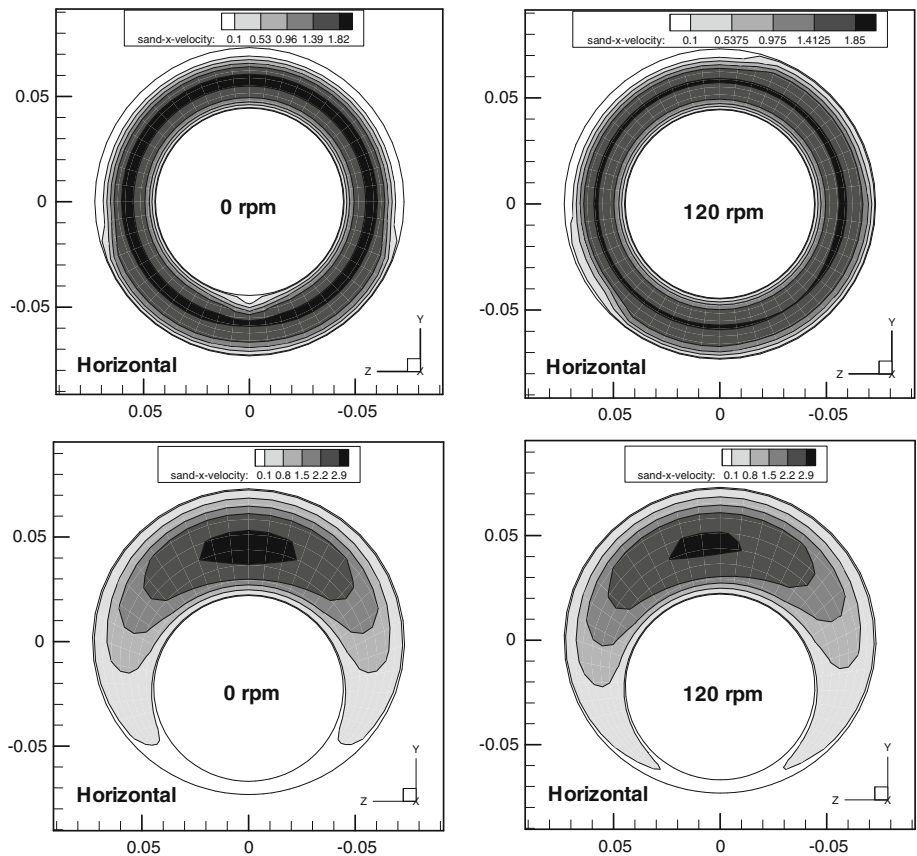

Fig. 9 Pipe rotation effect on the cuttings velocity in both concentric and eccentric horizontal annulus (fluid velocity = 5 ft/s, foam quality = 90 %)

The 3D CFD simulation was conducted for the liquid–solid mixture flow through both concentric and eccentric annuli which represent the cutting transport in foam drilling. Navier–Stokes and continuity equations coupled with the PL rheological model were used for the modeling.

The simulations were conducted for various foam velocities, foam qualities, pipe rotations, and well deviations. The CFD simulated cuttings transport results agree

well with the experimental data. The cuttings transport ratio increases with the increasing of the foam quality, foam velocity, and drill pipe rotation. For 80 % foam quality, the relative increase in cuttings transport ratio was about 9.5 % as foam velocity increased from 2 to 5 ft/s in concentric annulus, while other parameters were maintained constant. As foam quality increased from 80 to 90 %, the cuttings transport increased from 0.718 to 0.75 for a constant velocity of 2 ft/s in concentric annulus. For 90 % foam quality, the cuttings transport ratio increased from 0.72 to 0.79, while the pipe rotation increased from 0 to 120 rpm for a foam velocity of 2 ft/s in eccentric annulus. The cuttings transport ratio decreases with a larger angle of deviation from 0° to 45° from vertical. For 90 % foam quality, the cuttings transport ratio decreased from 0.98 to 0.81 when the deviation increased from 0° to 45° from vertical for a foam velocity of 5 ft/s in concentric annulus. The ratio remains constant (or slightly varies) between 45° and 90°. The study of this paper indicates the reliability of CFD simulation in modeling the effects of complex physical processes.
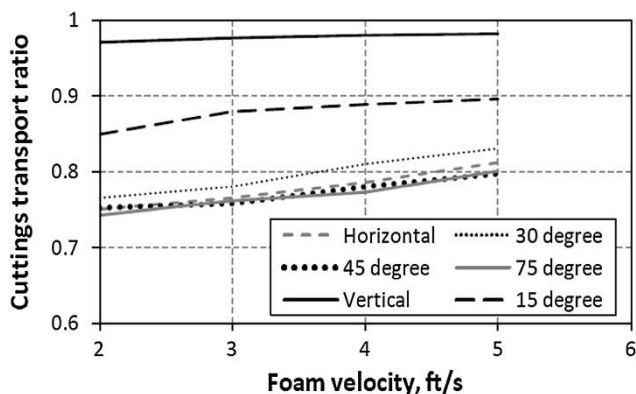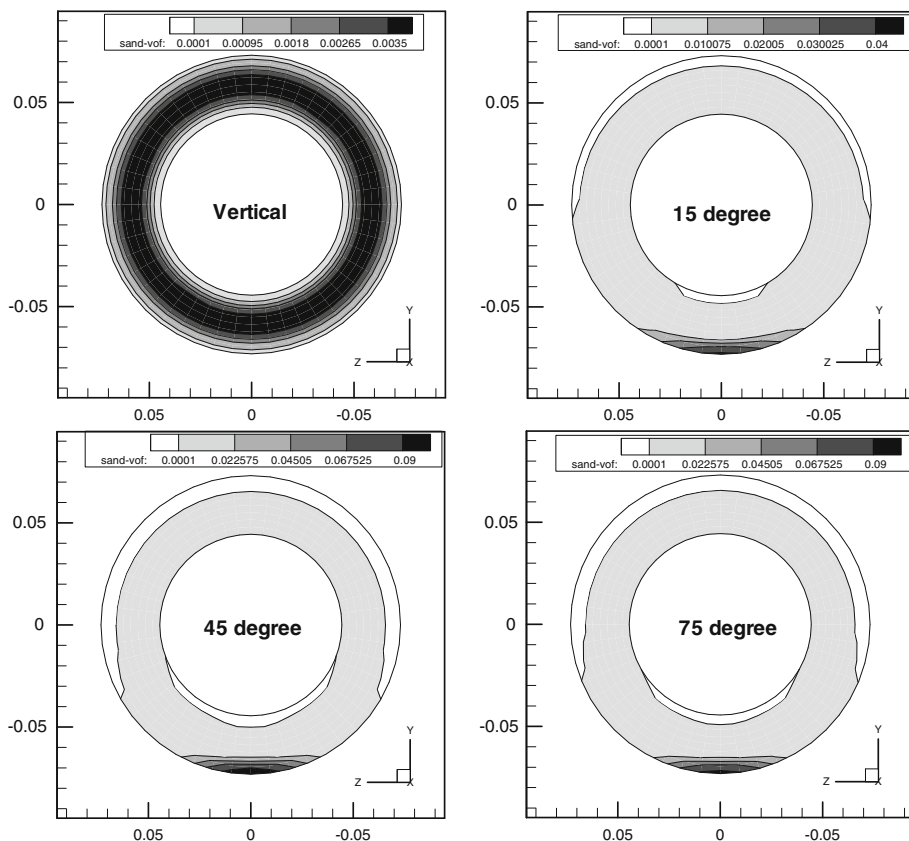
Fig. 10 Effect of well deviation on the cuttings transport ratio in the concentric annulus (foam quality = 90 %)

Fig. 11 Effect of the deviation angle on the cuttings volume fraction in the concentric annulus (fluid velocity = 5 ft/s, foam quality = 90 %, no pipe rotation)

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