AADE-20-FTCE-SPP-08

CFD Approach to Investigate the Effect of Mud Rheology on Cuttings Removal in Horizontal Wells

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Abstract

Cuttings transport is one of the major challenges in horizontal and extended reach wells. A computational fluid dynamics (CFD) model is developed to explore the effect of mud rheology on cuttings transport in horizontal wells.

CFD Model (Eulerian-Eulerian) approach is utilized to simulate cuttings transport in the annulus under transient conditions. Numerical simulation results were validated by experimental data from literature review. Different drilling fluids were investigated to evaluate their performance on cuttings removal on horizontal wells. A comparative study was performed to predict optimum fluid property that can evaluate fluid performance on cuttings transport while drilling.

The developed CFD model shows an acceptable agreement with the experimental work, and can accurately estimate the annular frictional pressure loss and solid concentration. It was observed that cuttings removal from the narrow side (low side) of horizontal section are enhanced by using low viscosity mud or water over medium and high viscosity mud. Drillstring rotation has strong impact on enhancing cuttings transport on this narrow area especially when high viscosity mud is used. Drillstring rotation can improve hole cleaning in horizontal wells till certain limit. In this study, increasing drillstring rotation above 200 RPM did not improve cuttings removal and hole cleaning. It was observed that the best way to improve the transport efficiency of non-Newtonian drilling fluids flowing in a laminar flow in horizontal wells is to keep high yield point/plastic viscosity (YP/PV) ratio. While in turbulent flow, it is recommended to keep the ratio of flow behavior index/flow consistency index (η/K) high for better hole cleaning.

1. Introduction

Drilling fluids (drilling mud) are used in rotary drilling to: control wellbore formation pressure, remove cutting outside the annulus, cool and lubricate the bit and maintain wellbore stability. Cuttings transport is the process of circulating rock fragments cut by the bit from bottomhole through annulus between drillstring and wellbore to the surface. In vertical or near vertical wells, cuttings transport is assessed by settling velocity. Rock fragments will be transported outside the hole as long as fluid axial velocity is greater than cutting slip velocity. On the other hand, cuttings transport is more complex and challenging in deviated and horizontal wells than vertical wells.

Cuttings Transport become a major challenge in extended reach wells with a long horizontal section nowadays. Poor hole cleaning can lead to high torque and drag, fast bit wears, poor cement jobs and slow rate of penetrations; and can end up in stuck pipe and loss of the well. Iyoho (1980) made a very comprehensive study about cutting transport in directional and horizontal well. He conducted several experiments on long flow loop pipe (40 ft.) to observe the effect of fluid velocity, hole inclination, pipe rotation, eccentricity, and mud rheology on hole cleaning. He concluded that fluid circulation rate, hole inclination and mud rheology were the major factors impacting hole cleaning in directional wells. Yu et.al (2004) showed that four forces are acting on the cuttings while circulating in the annulus: downward gravitational force, upward buoyant force, drag force parallel to the flow and lift force perpendicular to the flow. He performed his tests on a beaker to examine the effect of chemical surfactant, particle size and fluid PH on cutting transport. He found that adding chemical surfactant helped in circulating cuttings through the entire length of the loop scale cutting transport in horizontal pipe. Duan et.al (2006) reported that smaller cuttings are difficult to circulate out of the hole compared to larger ones when water was used as the circulating fluid. He also showed that pipe rotation and mud rheology were major factors for cutting transport in horizontal wells. Okrajni and Azar (1986) studied the effect of mud rheological properties on cuttings transport in directional wells. Experiments were conducted on water and bentonite/polymer mud at different inclination from 0 to 90 degrees. He examined the effect of drilling fluid plastic viscosity (PV), yield point (YP), and apparent viscosity (AV) on hole cleaning. He concluded that using high ratio of (YP/PV) provides efficient hole cleaning only when the flow is laminar. While in turbulent flow, mud rheological properties was insignificant for hole cleaning. Luo et.al (1992) developed a physical models based on the different forces acting on the solid particles and four dimensionless group. He validated his model by data from 8-1/2", 12-1/4" and 17-1/2" holes from the field. He concluded that decreasing fluid viscosity in turbulent flow improves cutting removal in deviated wells. Terry et.al (1996) conducted a comparative study on the capability of water and oil based mud on hole cleaning. He conducted several experiments on 5-in flow loop with 2-3/8-in inner diameter with 0.62 eccentricity. He used limestone cuttings and different type's oil and water base mud. He showed that flow diversion from under the pipe in high angle wells is controlled by the fluid's flow index n and flow diversion is less affected at low and intermediate angles. He also showed that water base and oil base muds clean the well similarly under the same rheological properties and velocity.

On the other hand, Tomren et.al (1986) reported that low viscosity in turbulent flow regime perform similarly to high viscosity fluid in turbulent flow in inclined annuli. His study was very important, because he used long test section (40 ft) to ensure establishment of steady flow and cover wide ranges of inclination from 0 to 90 degrees. Ford et.al (1990) performed a comprehensive study on different drilling parameters required to ensure good hole cleaning. A laboratory setup of 21 feet with inner tube size 3.5-in and 2.4-in diameter that can orientated at any angle was used for this purpose. He found that increasing fluid viscosity improves cutting removal for cutting rolling and suspension mechanisms when using high or medium fluid viscosity. He also reported that drillstring rotation did not improves cutting transport when using water. Moreover, Pedan et.al (1990) showed the bad performance of medium viscosity fluid on cutting removal when compared to low viscosity and high viscosity fluids. This was opposed with what was observed by Piroozian et.al (2011) that medium viscosity fluid perform much better in cutting removal than high viscosity mud in directional wells.

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical solution methods to solve fluid flows. CFD modeling is used to gain insight and understand of flow regimes, holdups and size distributions. This why, a CFD model was developed in this paper to analyze cuttings transport phenomenon on horizontal wells. Bilgesu et.al (2007) developed a CFD model showing that high flow rate and drillpipe rotation has more cleaning effect for smaller particles compared to larger particles in horizontal wellbore. Han et.al (2010) examined the impact of annulus inclination and drillpipe rotation on particle rise velocity, pressure drop, and drilling fluid carrying capacity by performing different experiments and numerical tests. He concluded that particle rise velocity will be misleading to evaluate cutting transport phenomena due to bed formation and flow area reduction. Sun et.al (2014) conducted a numerical study on solid-liquid transport phenomena at different wellbore inclination, rotational speed and flow rate. He noted that pipe rotation significantly increases drilling fluid tangential velocity leading to generate drag force that helps in cutting suspension. In addition, he proposed empirical correlation for pressure drop and cutting concentration. Akhshik et.al (2015) coupled CFD and Discrete Element Method (CFD-DEM) to simulate cuttings transport considering the dynamic collision process. He successfully showed on his model particle suspension at low inclinations and rolling behavior at high inclination. Dewangan and Sinha (2016) utilize Eulerian approach to model cuttings transport behavior in concentric annulus with inner cylinder rotation. He found that amount of turbulence was least at the middle of borehole wall and maximum at some distance from inner and outer cylinder. He also noted there is strong relation between slip velocity and mixture total kinetic energy. Omid et.al (2017) developed a CFD model to study the effect of eccentric annuluses on cutting accumulation. He found that drillpipe eccentricity can aggravate cutting accumulation due to reduction of the flow area available for cutting leading to its settlement. Moreover, he noticed that drillstring rotation impact on improving hole cleaning is more effective with high eccentric annulus due to drag force effect and dispersion of the cutting. Epelle and Dimitrious (2018) conducted a numerical study to investigate cutting transport phenomena in steady state and transient condition under turbulent condition. Khaled et.al (2020) also showed the capability of CFD model to simulate liquid loading in gas wells. He concluded that liquid film flow reversal mechanism is the root cause of liquid loading in gas wells.

Finally, we can say that that there are many contradicting results reported from literature on the effect of fluid rheology on hole cleaning of horizontal wells. In addition, limited number of papers were published using numerical models to study fluid rheology effect on cutting transport. Up to date there is unresolved question regarding the selection of the favorable fluid rheology while drilling and how one can evaluate the quality of mud rheology while drilling if it's efficient for hole cleaning or not?

2. CFD Model

A three dimensional model is developed to study the effect of mud rheology on cuttings transport in horizontal pipe based on computational fluid dynamics (CFD). Eulerian-Eulerian approach is utilized to describe the behavior of multiple, separate and interacting phases. The continuous phase and dispersed phase are assumed to be interpenetrating continua in the Eulerian approach. Eulerian approach was selected, because solid volume fraction in this analysis was expected to be higher than 0.1; and the particle-particle interactions and particle volume fraction on the continuous cannot be neglected. Therefore using Eulerian-La grange discrete phase model (DPM) was being omitted. The flow description consists of two differential equations describing the conservation of mass, momentum in equation (1) - (3) that need to be solved. These equations are the continuity and the momentum equations presented by Van Wachem and Almsted (2003).

2.1. Continuity Equation

The continuity equation for both phases (liquid and solid phase) can be written as follows.

$$\frac{1}{\rho_{rs}}\left(\frac{\partial}{\partial t}(\alpha_s\rho_s)+\nabla.(\alpha_s\rho_s\overrightarrow{v_s})=\sum_{l=1}^{n}(\dot{m}_{ls}-\dot{m}_{sl})\right) \qquad (1)$$

2.2. Momentum Equations

Fluid-Fluid Momentum conservation equation

$$\frac{\partial}{\partial t}(\alpha_l\rho_l\overrightarrow{v_l}) + \nabla.(\alpha_l\rho_l\overrightarrow{v_l}\overrightarrow{v_l}) = -\alpha_l\nabla\mathrm{P} + \nabla.\tau_L + \alpha_l\rho_l\vec{g} + \sum_{s=1}^{n}[K_{ls}(v_l - v_s) + \dot{m}_{ls}\overrightarrow{v_{ls}} - \dot{m}_{sl}\overrightarrow{v_{sl}}] + (\overrightarrow{F_q} + \vec{F}_{lift,q} + \vec{F}_{wl,q} + \vec{F}_{vm,q} + \vec{F}_{td,q} \quad (2)$$

Fluid-Solid Momentum conservation equation

$$\frac{\partial}{\partial t}(\alpha_s\rho_s\overrightarrow{v_s}) + \nabla.(\alpha_s\rho_s\overrightarrow{v_s}\overrightarrow{v_s}) = -\alpha_s\nabla\mathrm{P} - \nabla\mathrm{P}_s + \nabla.\tau_s + \alpha_s\rho_s\vec{g} + \sum_{s=1}^{N}[K_{ls}(v_l - v_s) + \dot{m}_{ls}\overrightarrow{v_{ls}} - \dot{m}_{sl}\overrightarrow{v_{sl}}] + (\overrightarrow{F_q} + \vec{F}_{lift,q} + \vec{F}_{wl,q} + \vec{F}_{vm,q} + \vec{F}_{td,q} \quad (3)$$

2.3. Turbulence Model

The physics of the flow, accuracy level and computational time are the main factors for selecting the appropriate turbulence models. Three basic approaches can be utilized to compute any turbulent flow: direct numerical simulation, large eddy simulation and Reynold-averaged Navier-Stokes simulation (RANS). RANS approach is the most popular method for industrial flow. It is based on solving the time averaged of Navier-Stokes equations and all turbulent motion is modeled. It had different models such as the two equations models: $\kappa - \varepsilon$, $\kappa - \omega$, and Reynold stress model (RSM).

The $\kappa - \varepsilon$ model is based on modeling transport equations, kinetic energy (κ) and dissipation rate (ε). The $\kappa - \varepsilon$ model has been widely used for engineering flow calculations, because of its robustness and reasonable accuracy wide ranges of turbulent flows as recommended by Fluent (2013). Shih et.al (1995) proposed $\kappa - \varepsilon$ realizable model by adopting new eddy-viscosity formula and overcoming the deficiency of the standard model in modeling dissipation rate. This why the realizable $\kappa - \varepsilon$ was considered suitable for turbulent flow in this study. Besides solving the continuity and momentum equations; different equations for solid-liquid multiphase flow were also solved and summarized in table 1.

Table 1: Models used for solid-liquid multiphase flow

Solid-liquid properties	Closure model
Particle Drag	Gidaspow (1994)
Particle Lift	Saffman-Mei (1994)
Granular Viscosity	Syamlal et.al (1993)
Granular Bulk Viscosity	Lun et.al (1984)
Granular Temperature	$\theta_s = \frac{1}{3}(v_{sl}.v_{sl})$
Solid Pressure	Lun et.al (1984)
Radial Distribution	Lu et.al (1984)

2.4. Geometry and Flow Condition

Cuttings transport in extended reach wells can be for thousands of feet, but simulating multiphase flow for this long medium will be very time consuming. So pipe length selected for this numerical simulation was long enough to ensure fully developed flow and longer than hydrodynamic entrance length based on equations proposed by Yunus and Cimbala (2006)

$$L_{h,laminar} = 0.05\,(D_{hole} - D_{pipe})N_{RE} \quad (4)$$

$$L_{h,turbulent} = 1.359\,(D_{hole} - D_{pipe})(N_{RE})^{\frac{1}{4}} \quad (5)$$

$$N_{RE} = \frac{\rho_l D_h^{\eta} \nu^{2-\eta}}{K\left(\frac{3\eta+1}{4\eta}\right)^{\eta} 8^{\eta-1}} \quad (6)$$

where N_{RE} is Reynold number as suggested by Madlener et.al (2009).

$$D_h = D_{hole} - D_{pipe} \quad (7)$$

where ν is the bulk flow velocity, η is the power law flow behavior index, K is the power law consistency index, and D_h is the hydraulic diameter.

The flow geometry utilized in this study is a horizontal pipe of 2m length with two walls. The outer wall is stationary and has a diameter (D_o) equals 0.0739m and represents the wellbore. While the inner wall represents the drillstring used while drilling with a diameter (D_i) 0.047m. Inner wall was kept either in stationary or in a rotation mode based on the analysis done. Since drillstring in deviated and horizontal wells have the tendency to lay down on wellbore low side due to gravity. Therefore, annuli eccentricity (E) is assumed to be equal 0.6.

$$E = \frac{2e}{D_{hole} - D_{pipe}} \quad (8)$$

where e is the distance between outer and inner pipe.

Simulation input parameters were obtained from the work of Osgouei (2010) and are summarized in table 2. Nine different drilling fluids were adopted in this model inspired from Iyoho (1980) and Okrajni and Azar (1986) to examine the effect of fluid rheology on cutting transport in horizontal well profile. Fluid rheological constants are summarized in table 3. Power law model was used to describe the non-Newtonian fluid rheology based on equation.

$$\tau = K\,\gamma^{\eta} \quad (9)$$

where η is the power law Flow behavior index, K is the power law consistency

2.5. Mesh Independence Study

Hexahedral mesh were implemented in all flow conditions. In CFD calculations, the viscous layer (immediately adjacent to the wall) and the log-layer (slightly further away from the wall) are very important factors in turbulent flow regime. Because fluid velocity changes rapidly near the wall. This is why three inflation layers were added as shown in fig. 1 and a good estimation of first layer grid was done for every simulation runs to keep Y^+ constant above 30 based on recommendation by Ansys Fluent (2013) for accurate computational results from the Realizable $\kappa - \varepsilon$ model.

$$Y^+ = \frac{y}{\mu}\sqrt{\rho\tau_w} \quad (10)$$

where y is the first layer thickness (difference between wall and cell center), and τ_w is the wall shear stress.

Table 2. Simulation input parameters

Geometry	
Hole diameter (m)	0.0739
Pipe diameter (m)	0.047
Drillstring Length (m)	2
Particle properties	
Cutting density (kgm^{-3})	2761.4
Cutting Diameter (m)	0.00201
Porosity	0.36
Drilling Parameters	
Drilling fluid velocity (ms^{-1})	1.375
Rate of penetration ROP (ms^{-1}) / (fthr^{-1})	0.00508 (60)
Drillpipe Rotation (RPM)	0 - 300
Hole eccentricity, E	0.623
Wellbore inclination (degrees)	90

Table 3: Fluids Rheological Properties

Fluid	Density, Kgm^{-3}	η	K (Pas^{η})	Flow regime
Water	998.7	1	0.001	Turbulent
Low Viscosity Bentonite (LVM)	1006.5	0.68	0.04	Turbulent
Medium Viscosity Mud (MVM)	1006.5	0.61	0.209	Transitional
CARBOP-OL (CARB)	1012.5	0.64	0.283	Laminar
High Viscosity Bentonite (HVM)	1018.5	0.61	0.44	Laminar
Fluid 1	1012.5	0.74	0.049	Turbulent
Fluid 2	1012.5	0.59	0.088	Turbulent
Fluid 3	1018.5	0.42	1.044	Laminar
Fluid 4	1018.5	0.74	0.33	Laminar

A mesh independence analysis was conducted to determine the optimum number of elements for accurate solutions with the least possible computational time. It was observed that pressure calculations stabilized starting from 78800 elements as show in fig. 2. So it was decided to use a mesh grid with element size 0.0002m, and a first layer thickness equals to 0.001m. Mesh properties used in this study are summarized in Table 4. To investigate solid particles behavior while circulating inside the annulus between the two walls, the designed geometry was divided into four main planes as shown in fig. 3. So that the radial distribution of fluid properties (velocity, and volume fraction) can be observed. Plane 1 represents the wide region between the top of the drillpipe and wellbore, while plane 3 represents the narrow gap between drillpipe and hole.

2.6. Model Boundary Conditions

The inlet of the cuttings and drilling fluid were assumed as velocity inlet and pressure outlet at atmospheric. No slip boundary condition is considered between the continuous phase and the walls (inner and outer pipe). Inlet volume fraction was calculated based on the equations proposed by Larsen et.al (1997) and Ozbayoglu et.al (2010).

$$C = \frac{ROP\ (1-\phi)}{\left(1-\frac{D_{pipe}}{D_{hole}}\right)^{2} V_{cut}} \tag{11}$$

Where ROP represents drilling rate of penetration, and ϕ is the rock porosity, C is the cuttings concentration.

$$C = \frac{Net\ volume\ Occupied\ by\ particles}{Total\ volume\ of\ annulus} \tag{12}$$

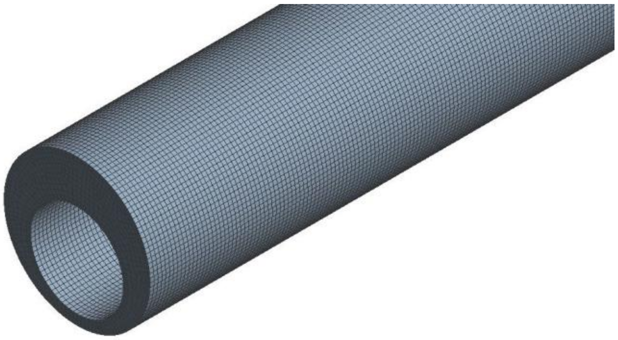

Fig. 1 Computational 3D Mesh for flow condition

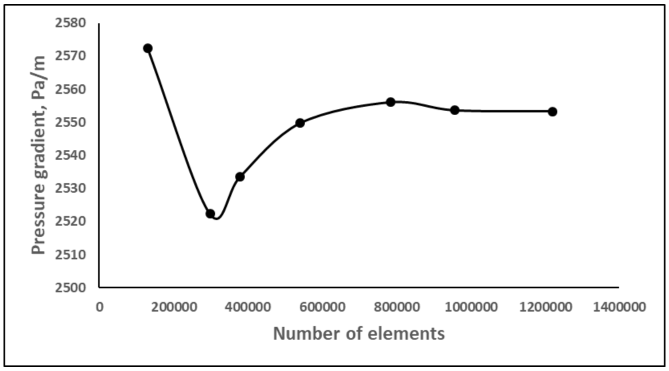

Fig. 2 Mesh independence study

Table 4: Mesh properties

Element Size (m)	0.002
Number of elements	788000
First Layer thickness (m)	0.001
Minimum orthogonal quality	0.61
Maximum skewness	0.6
Maximum aspect Ratio	1.07

2.7. Simulation Strategy

In this study, the CFD model has been solved numerically using finite volume formulation using ANSYS Fluent 2019 R3. Pressure based solver was adopted and the phase coupled SIMPLE (semi-implicit method for pressure linked equations) was used to solve fluid flow equations. Second order implicit scheme was utilized to solve momentum equation and first order scheme was discretized to solve volume fraction, turbulent kinetic energy and turbulent dissipation rate for turbulent flow. Transient state was assumed due to complexity of solving multiphase transport equations and achieving acceptable convergence under steady state. A time step size of 0.0005 was used and 10^{-4} convergence criterion was set for all equations solved. Each simulation test was run for total flow times of 3.5 seconds using Texas A&M high performance research computing (Ada Cluster - Intel x86-64 Linux) with 18 cores and 64 GB RAM.

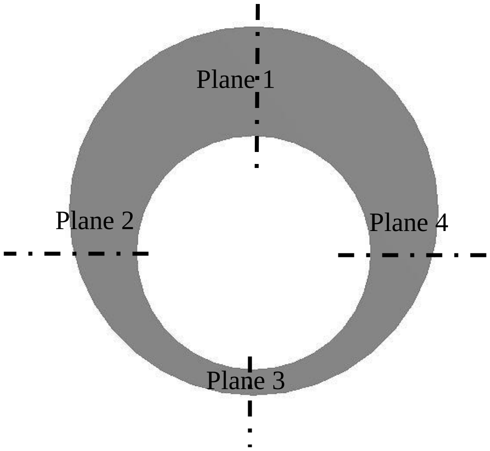

Fig. 3 Geometry Set-up with line planes

3. Results and discussion

3.1. Model Validation

The CFD model was validated with the experimental data of Osgouei (2010) summarized in table 5. CFD results show a good agreement with experimental data. It predicts pressure loss in the annulus with a mean error equals 8.14% and can successfully estimate the solid volume fraction with an average error equals 7.61% as shown in fig. 4 and 5. These prove the ability of the developed CFD model to provide an accurate results.

3.2. Fluid rheology

The main objective of this study is to investigate the effect of fluid rheology on cuttings transport in horizontal wells. Water and low viscosity mud (LVM) used in this analysis are flowing in turbulent flow regime while circulation. While laminar flow regime was studied by using high viscosity mud (HVM) and Carbopol (CARB). In addition the medium viscosity mud (MVM) is in transitional flow behavior ($2100 < N_{Re} < 4200$). The numerical simulation output results are solid axial velocity and concentration (volume fraction) along the radial distribution of planes 1-4. Solid axial velocity and volume fraction contours are presented for visualization of drillpipe rotation effect on hole cleaning. It is important to point out that solid axial velocity reported in this study is normalized to the bulk flow velocity.

Table 5: Experimental data - fluid and geometry characteristics

Geometry	
Hole diameter (m)	0.0739
Pipe diameter (m)	0.047
Drillstring Length (m)	6.4
Fluid Properties	
Fluid type	Water
Density (kg/m^3)	998.5
Flow behavior index, $\boldsymbol{\eta}$	1
Consistency index, $\boldsymbol{K}$ ($\boldsymbol{Pas^{\eta}}$)	0.001
Particle properties	
Cutting density (kgm^{-3})	2761.4
Cutting Diameter (m)	0.00201
Porosity	0.36
Drilling Parameters	
Drilling fluid velocity (ms^{-1})	1.21-1.83
Rate of penetration ROP (ms^{-1}) / (fthr^{-1})	0.00508 (60)
Drillpipe Rotation (RPM)	0
Hole eccentricity, E	0.623
Wellbore inclination (degrees)	90

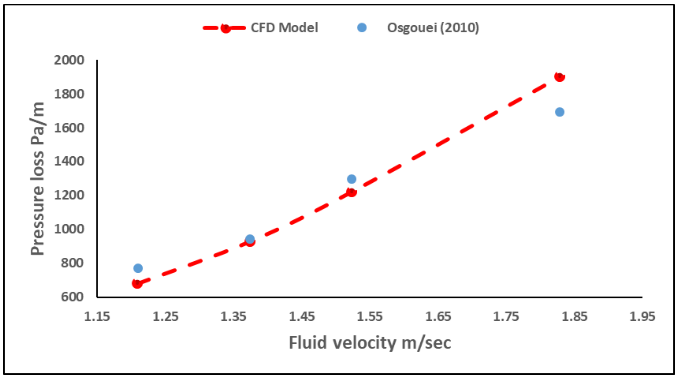

Fig. 4 Validation of CFD model against experimental data

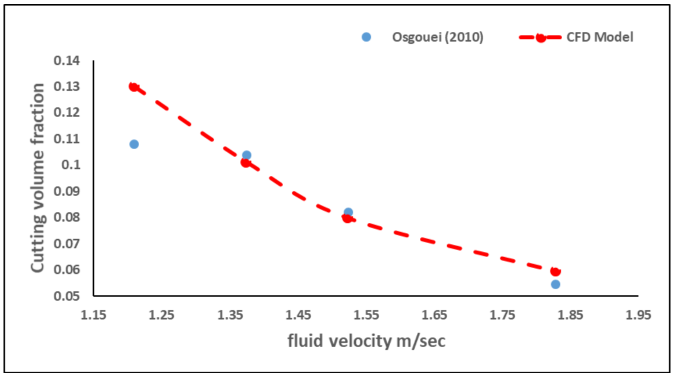

Fig. 5 Validation of CFD model against experimental data

Fig. 6 shows the solid volume fraction across the four planes. It demonstrates that the maximum cuttings (solid) concentration with all drilling fluids are observed on plane 3 (narrow part of the annulus). This can be related to the gravity impact that aggravates solid slip, phase segregation, and eventually leads to bed accumulation. The maximum cuttings concentration (0.63) was reported when HVM or CARB mud was used as a circulating fluid. On the other hand, water and LVM seem to be more efficient on hole cleaning and cuttings cleanout operation with less solid concentration on plane 3. High solid volume fraction on the narrow section can be attributed to pipe eccentricity and fluid flow regime. Pipe eccentricity occurs in high inclination wells, because drillstring tends to lay down on the wellbore low side due to gravity effect. Okrajni and Azar (1986) showed that pipe eccentricity impact is more noticeable at high wellbore inclination (55-90). Pipe eccentricity leads to uneven distribution of velocity profiles across wellbore section. Fluid will flow faster in the wider region than the narrower part. So cuttings accumulation will increase in the narrower part and cutting bed removal become difficult due to this flow diversion. In addition to pipe eccentricity, fluid flow regime is a very important factor for hole cleaning. Although HVM and CARB flow in a laminar flow regime that is very efficient in cuttings suspension and cuttings removal in vertical wells; this merit reduces and vanishes when wellbore inclination reaches 90 degrees. Because the fluid drag force will be perpendicular to the gravitation force and will have a very small effect to compensate this gravitational force. On the other hand, LVM and water flow in turbulent flow regimes that has a chaotic fluid movement allows the transfer of momentum and velocity distribution more uniformly than laminar. So, drilling fluid will penetrate the narrower part more effectively and decrease the effect of flow diversion resulted from hole eccentricity. In addition to that, fluid in turbulent flow increases frictional pressure loss resulting on inducing more shear stress across the bed surface and eventually helping on cutting bed removal. These findings agree with the experimental results reported from Ozbayoglu et.al (2009) and Mohammadsalehi et.al (2012) that Increasing liquid viscosity will increase bed area and increase the required flow for hole cleaning.

It is observed that there is a slight increase of solid concentration in plane 2 when LVM and water are used as a circulating fluid accompanied by low solid axial velocity in this area. This can be due to the turbulent flow behavior of LVM and water. There is also asymmetry profile of solid concentration curves between plane 2 and 4 in case of water and LVM. Solid volume fraction in all planes are distinct with off center peaks. Solid particles tends to be lower near the walls and maximum at the center. This proves that solid cuttings tend to travel in the center of the annulus during mud circulation similarly to fluid flow behavior of non-uniform fluid distribution. It is important to point out that although water is very efficient in cleaning the narrow part (low side) of horizontal pipe due to its low viscosity and turbulent flow initiation at low flow rates. It is preferable to use low viscosity non-Newtonian fluids than water that had yield stress and thixotropic property for efficient hole cleaning.

Figure 7 demonstrates solid axial velocity across the four planes. It shows a clear symmetry of axial velocity profiles across plane 2 and 4 for laminar flow that is reflects on solid volume fraction figures. Besides that, a high axial velocity in plane 3 with LVM and water is noticed that is another evidence of hole cleaning enhancements. It is also observed there is a clear asymmetric profiles of axial velocity across all planes of LVM and only on plane 1 and 3 for MVM, HVM and CARB. This observation supports the previous conclusion on the impact of pipe eccentricity and flow diversion on cuttings accumulation on the narrow side of the wellbore.

3.2. Effect of drillstring rotation

Since HVM study was the worst mud rheology compared to other fluids for cuttings transport as indicated in the previous section. Drillstring rotation effect on enhancing or aggravating HVM performance for cuttings transport was examined. The outer wall is assumed as stationary wall, while the inner will rotate in clockwise direction to simulate drillstring rotation in wellbore.

It was noticed that cuttings concentration was dramatically reduced in the narrow part of the eccentric annulus as shown in fig. 7 and solid volume fraction contours in fig. 9 when inner cylinder rotation increased. This is attributed to the increase of drilling fluid tangential velocity when drillpipe rotates leading to generation of more drag force on cuttings bed and enhancing cuttings removal. Besides that, Epelle and Dimitrios (2018) showed that drillpipe rotation leads to shear thinning behavior of the non-Newtonian fluids with viscosity variation around the annulus. This phenomenon can also help in limiting flow diversion occurrence across the eccentric annulus and allow more cuttings transport.

Solid concentration in fig. 7 increases in all planes except plane 3 with more drillpipe rotations. This is can be visualized from the area under the curves of all planes. This phenomenon occurs because when drillpipe rotates. It erodes cuttings bed and sway solid particles away against gravity from the narrow part (low side) to the wider areas. So solid concentration decreases on the narrow part of the annulus and increases on the other location. This can be clearly viewed in the solid volume fraction contours in fig. 9. Contours show that solid particles shifted away from the narrow part and distributed across the whole profile. It can be argued that drillstring rotation aids in keeping homogenous solid concentration around the pipe in the horizontal annulus. Cuttings fraction peaks (maximum value) shift away from inner pipe axis toward the outer wall due to rotational effect of mixing solid particles with liquid flow.

These curves also show that as drillstring rotation increases, cuttings concentration decrease until certain value of pipe rotation is reached. Above this value, reduction in solid concentration is negligible with more pipe rotation. This can be viewed from 200 & 300 RPM case, where no improvement in cuttings removal is recorded when rotation increased from 200 to 300 RPM. This observation also reported from Omid et.al (2017) and Pang et.al (2018) about drillpipe rotation impact for cuttings transport is negligible above certain point.

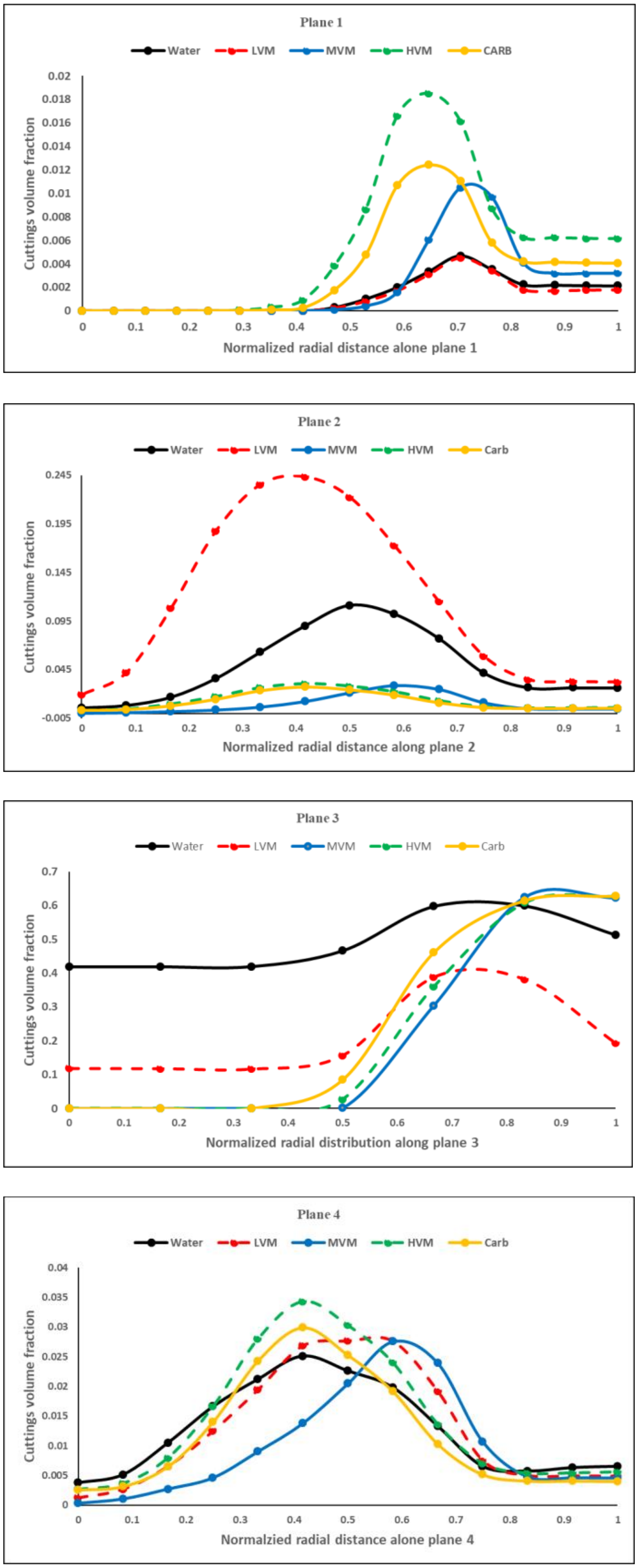

Fig. 6 Cuttings volume fraction profiles

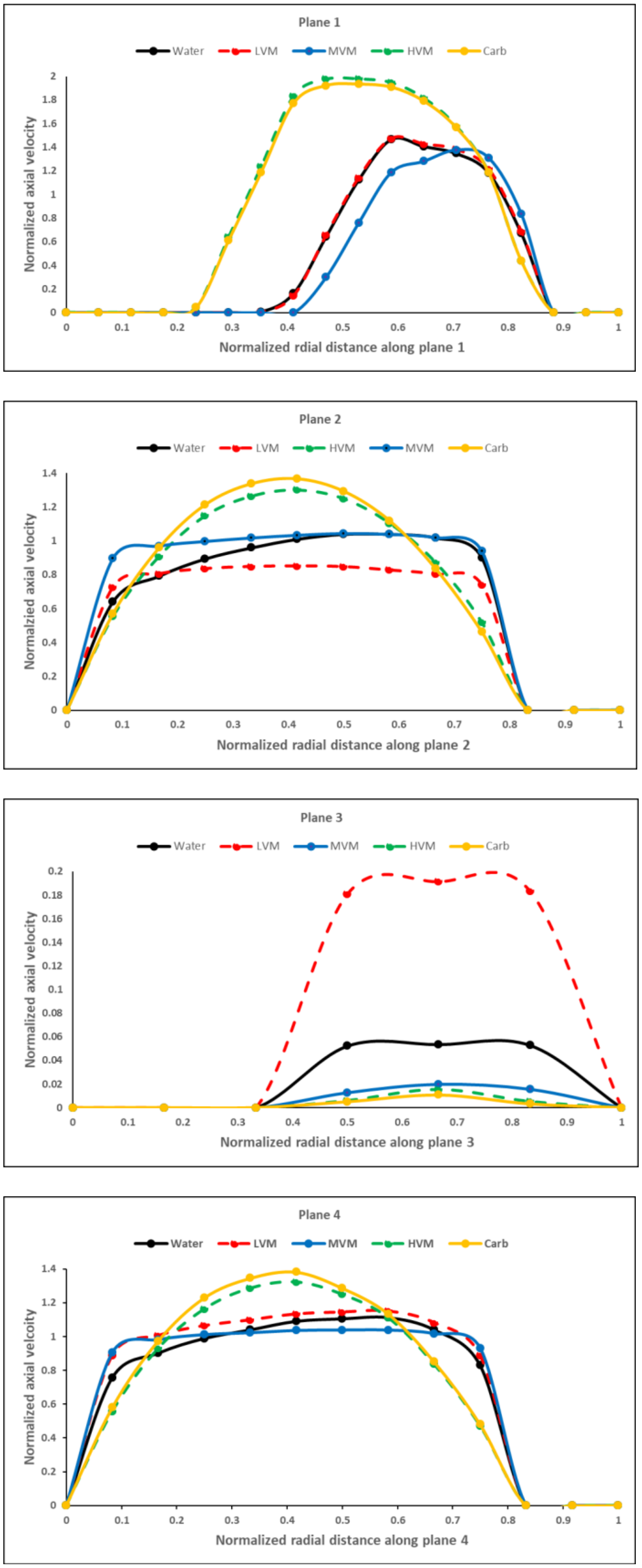

Fig. 7 Normalized axial velocity profiles

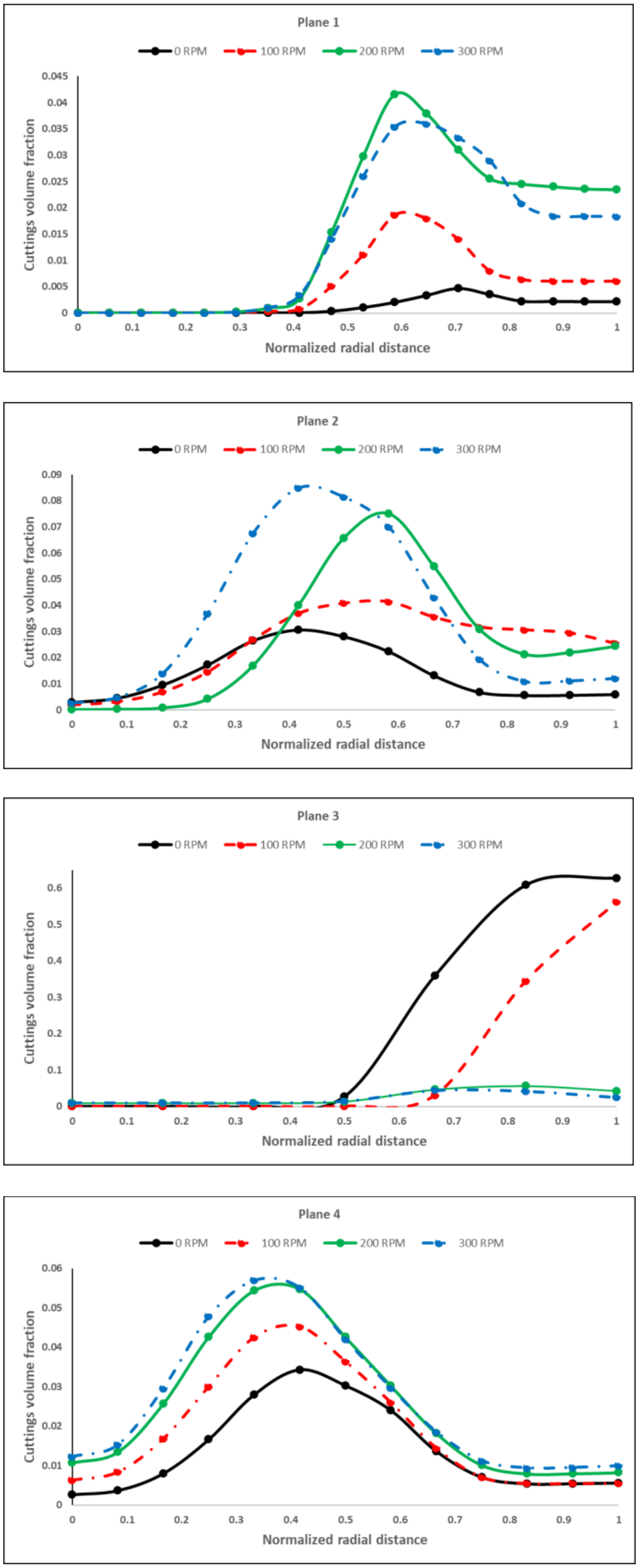

Fig. 7 Cuttings volume fraction for HVM at different RPM

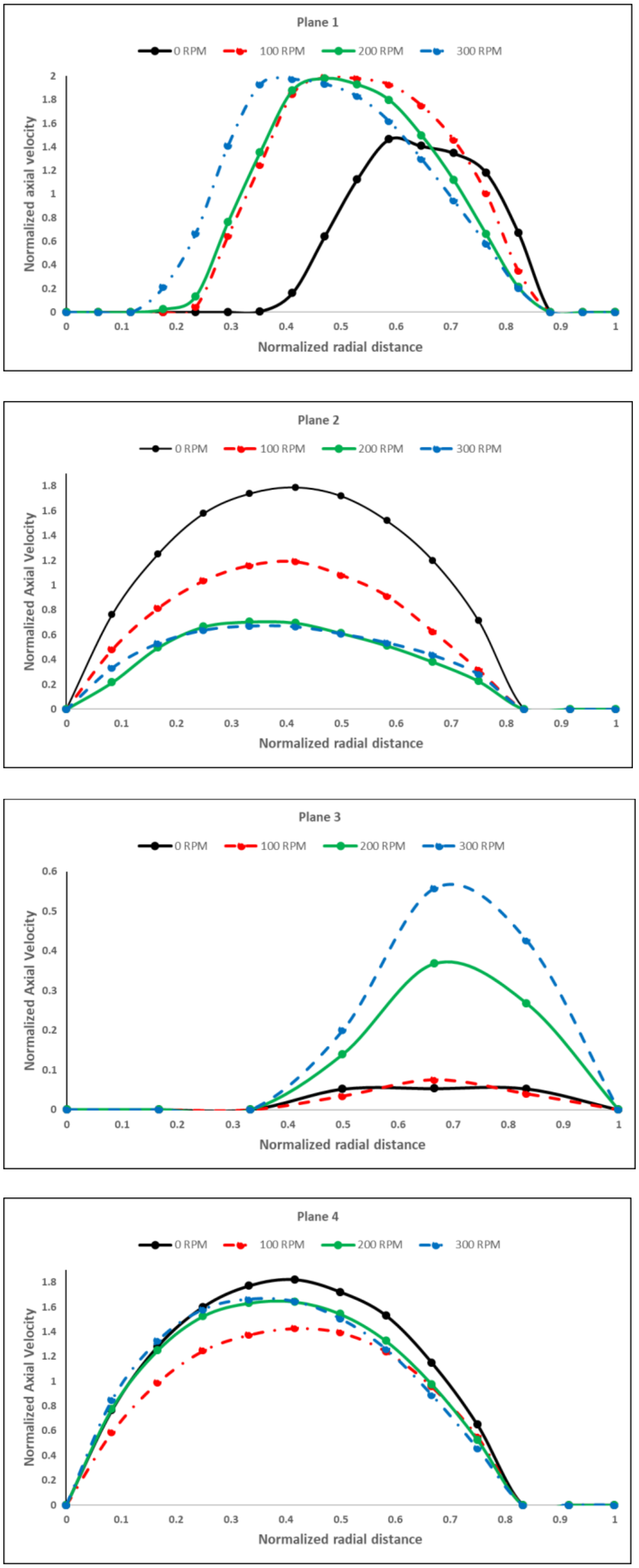

Fig. 8 Normalized axial velocity for HVM at different RPM

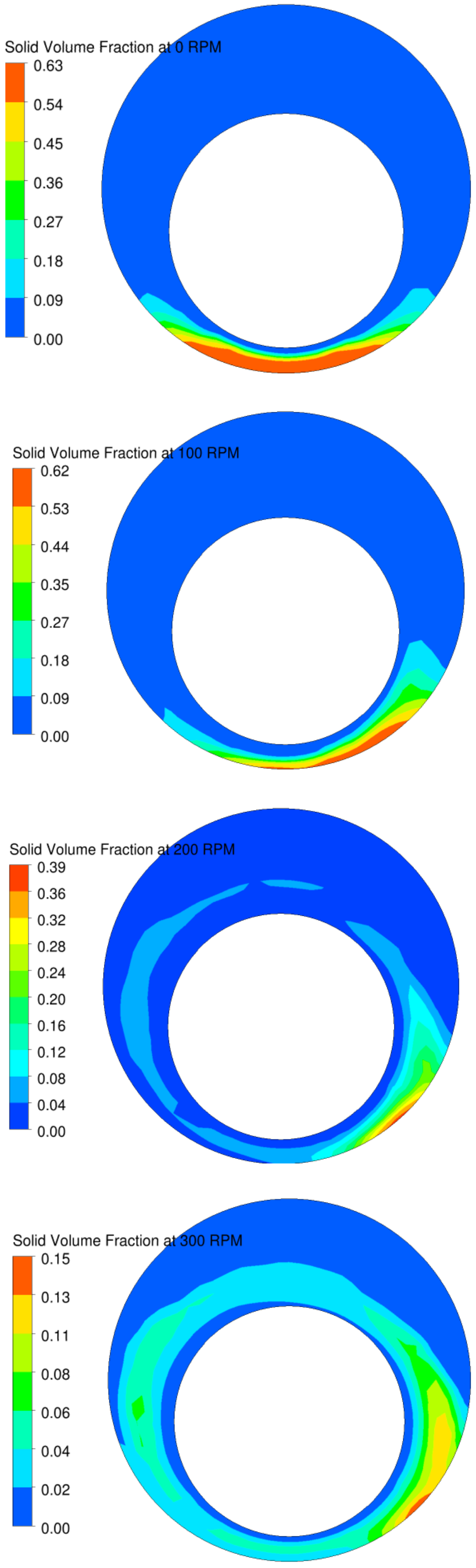

Fig. 9 Cuttings volume fraction Contours at different RPM

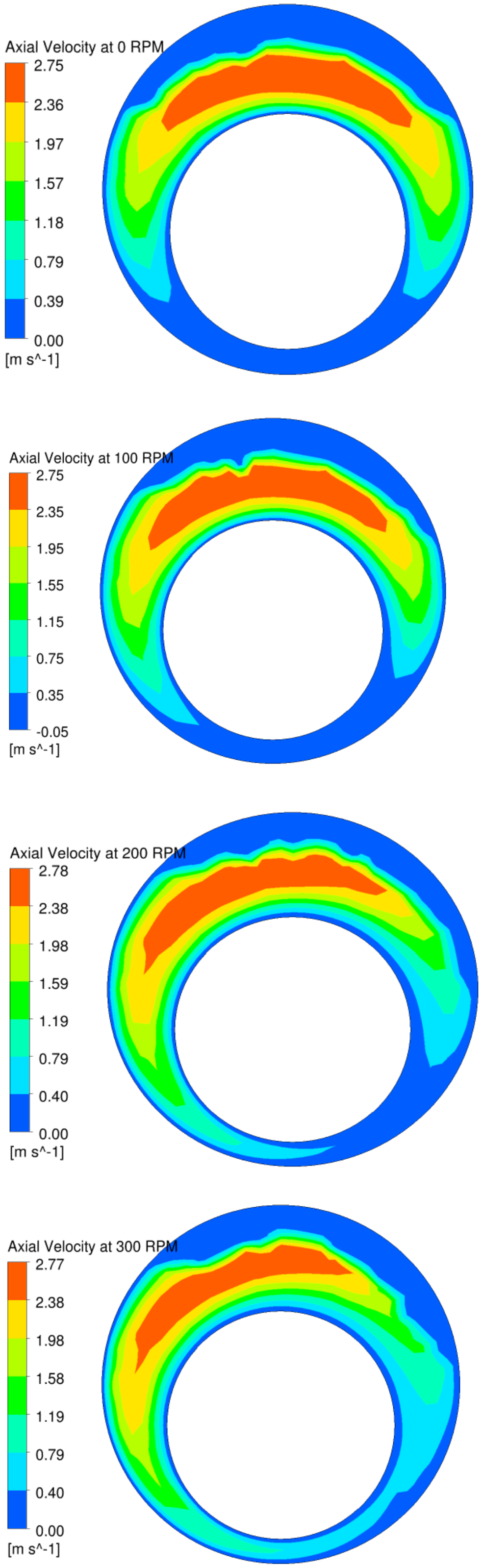

Fig. 10 Axial velocity Contours at different RPM

Table 6: Mud rheology comparison

Drilling fluid	Flow regime	U_e (Kg/m.s)	PV (CP)	YP/PV	η/K	Bed concentration
LVM	Turbulent	0.005161	3	0.67	16.91	0.30
Fluid 1	Turbulent	0.00907	6	0.5	14.92	0.31
Fluid 2	Turbulent	0.006144	3	1	6.64	0.34
MVM	Transitional	0.0172	9	0.89	2.93	0.36
Fluid 3	Laminar	0.0244	8	2	0.4	0.33
HVM	Laminar	0.030611	19	0.89	1.37	0.39
Fluid 4	Laminar	0.06064	40	0.5	2.2	0.42

Similarly, solid axial velocity increases at plane 3 and decreases in plane 2 and 4 due to increase in drillstring rotation as shown in fig. 8 and axial velocity contours in fig.10. This matches the previous conclusion about the impact of pipe rotation on applying extra stresses on cutting bed and divert the solid particles to other locations in the annulus away from the narrow part in the annulus. This is why solid axial velocity in plane 2 was clearly reduced with more pipe rotation due to more solid concentration. It is also noted that as pipe rotation increase, more increase in the asymmetry behavior of axial velocity across all planes.

3.3. Cutting removal and drilling fluid rheology

Based on the previous analysis, low viscosity fluids perform much better than high viscosity mud in cuttings transport on horizontal wells. But, what is the best approach drilling engineers on the oil fields can use to decide the optimum mud properties? or what is the best rheological parameter can be used to predict the fluid performance in cuttings transport if a hole cleaning problem is encountered? Therefore, different drilling fluid parameters were examined: effective viscosity (Ue), plastic viscosity (PV), yield point/plastic viscosity (YP/PV) ratio and power law flow behavior index/consistency index (η/K) ratio to study their impact on reducing or aggravating cuttings concentration on the well narrow side as shown in table 6.

After comparing previous fluid properties with the accumulated bed concentration located on the horizontal wellbore narrow area, it was observed that:

a- the best way to minimize the bed height when the flow is in turbulent or transitional regime is to keep η/K ratio high. η/K ratio of 15 or more shows a good cleaning effect in our case study. η/K ratio can be interpreted as inverse function of drilling fluid viscosity as reported by Adari et.al (2000). So high η/K ratio represents low fluid viscosity and strong turbulent flow. Fig. 11 shows that as η/K ratio decreases, cuttings accumulate and bed height increases in the wellbore low side.

b- Table 4 and fig. 12 show that for laminar flow, cuttings concentration decreases, when Ue or PV decreases or YP/PV ratio increases. These three variables can help in optimizing the efficiency of fluid rheology in cuttings transport under laminar flow regime. A ratio of 2 for YP/PV performs good in hole cleaning and cuttings removal in this study.

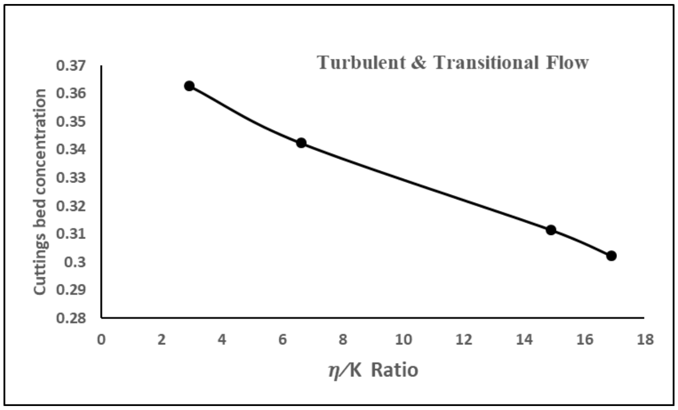

Fig. 11 η/K ratio vs cuttings bed concentration for turbulent flow

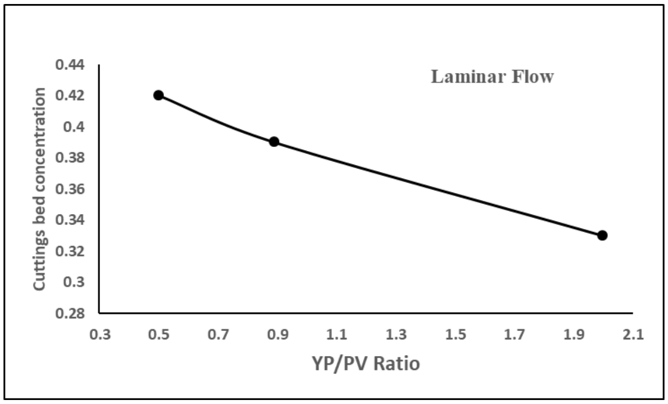

Fig. 12 YP/PV ratio vs cuttings bed concentration for laminar flow

Conclusions

- Low viscosity fluids and water are the optimum mud rheology for cuttings transport in horizontal wells
- Medium viscosity mud in transitional flow regime is better than high viscosity mud in laminar flow for horizontal hole cleanout.
- Drillstring rotation improves dramatically the cuttings transport performance of high viscosity mud in the narrow side of horizontal well (low side) due to increase of fluid tangential velocity leading to generating more drag force on cuttings bed and sway solid particles away from the narrow part to the wider areas.

- Drillstring rotation improves cuttings transport on horizontal wells until it reaches certain value. In this study, drillstring rotation with more than 200 rpm has negligible impact on improving hole cleaning.
- The best approach to cleanout horizontal wells flowing under turbulent flow regime is to keep η/K value high. In this study it was noticed that when η/K value approaches 15 or more, drilling fluids shows a good cleaning effect.
- For laminar flow it is advisable to increase YP/PV ratio or decrease effective viscosity and plastic viscosity values for efficient hole cleaning. In this study drilling fluid with YP/PV ratio of 2 was good enough to minimize bed accumulation.

Acknowledgments

This publication was made possible by the grant NPRP10-0101-170091 from Qatar National Research Fund (a member of the Qatar Foundation). Statements made herein are solely the responsibility of the authors.

The authors also thank Dr Muhammad Sami from Ansys Inc. for his help, valuable comments and suggestions.

We would like also to thank Alkassoum Ibrahim Toure from Texas A&M University for his help and suggestions on this research

The authors also thank the staff and workers at Texas A&M HPRC for their help and support while working on Tamu supercomputer.

Nomenclature

BHA	Bottomhole assembly
CARB	Carbopol mud
CFD	Computational fluid dynamics
D_{hole}	Hole inside diameter (m)
D_{pipe}	Drillpipe outside diameter (m)
DEM	Discrete element method
E	Hole eccentricity
e	Distance between outer and inner pipe
$\vec{F}_q$	External body force (N)
$\vec{F}_{lift,q}$	Lift force (N)
$\vec{F}_{wl,q}$	Wall lubrication force (N)
$\vec{\mathrm{F}}_{\mathrm{vm,q}}$	Virtual mass force (N)
$\vec{\mathrm{F}}_{\mathrm{td,q}}$	Turbulent dispersion force (N)
G	Gravitational acceleration (ms^{-2})
HVM	High viscosity mud
K_{ls}	Interphase momentum exchange coefficient
LVM	Low viscosity mud
$\dot{m}_{ls}$	Mass transfer from phase l to phase s (kgs^{-1})
$\dot{m}_{sl}$	Mass transfer from phase l to phase s (kgs^{-1})
MVM	Medium viscosity mud
N_{RE}	Reynold number
PV	Drilling fluid plastic viscosity
RANS	Reynold averaged Navier-Stokes simulation
RSM	Reynold stress model
RPM	Revolution per minute
ROP	Rate of penetration (ms^{-1})
$\overrightarrow{v_{sl}}$	Interphase velocity (ms^{-1})
$\overrightarrow{v_s}$	Solid Phase velocity (ms^{-1})
$\overrightarrow{v_l}$	Liquid Phase velocity (ms^{-1})
v_m	Mixture velocity (ms^{-1})
U_e	Drilling fluid effective viscosity (k/m.s)
y	Distance from wall to the cell center (m)
YP	Fluid yield point (Pa)

Greek Letters

ρ_{rs}	Phase reference density (kgm-3)
α_s	Solid phase volume fraction
α_l	Liquid phase volume fraction
ρ_s	Solid phase density (kgm-3)
ρ_l	Liquid phase density (kgm-3)
τ_s	Solid phase stress tensor
K	Kinetic energy
E	Dissipation rate
τ_L	Liquid phase stress tensor
τ_w	Wall shear stress (pascal)
θs	Granular Temperature (K)
μ_l	Liquid Viscosity (kgm-1s-1)
γ	Shear rate (s-1)
η	Flow behavior index
K	Consistency index (Pa.s^{n})
ν	Bulk flow velocity

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