



EFFECT OF DRILLING PARAMETERS ON DRILLING PERFORMANCE FACTORS IN HORIZONTAL WELLS USING SIMULATION APPROACH

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Abstract

The effect of drilling parameters on drilling performance factors in horizontal wells using simulation approach is studied in this paper. The inhomogeneous (Eulerian-Eulerian) model is employed to simulate a two-phase solid-fluid flow; the solid flow is the cuttings while the liquid flows are water and aqueous solution of sodium carboxymethyl cellulose (mud) respectively. The simulation was conducted using the workbench platform of ANSYS CFX 15.0. The focus is on evaluating the influence of fluid velocity, drill pipe rotation and fluid type on annular pressure loss and cuttings concentration when the diameter ratio and eccentricity are constant during horizontal well drilling. Results showed that at 80rpm, pressure loss simulations were slightly higher at fluid velocity of 2.743m/s as compared to prediction for water flow cuttings injection. Also, at fluid velocities of 1.524m/s to 2.438m/s pressure loss simulations were seen slightly higher as compared to prediction for mud flow with cuttings injection. As both water and mud velocities increased, the annular pressure loss also increased with mean percentage error of 9% and 13% deviation from ANSYS simulation for water and mud-cuttings transport respectively. It was observed that the cuttings concentration was highest with 16% when the annular velocity was at the lowest reading 1.524m/s for both water and mud-cuttings transport at 80rpm and 120rpm respectively. The comparison of cuttings concentration between ANSYS simulations for water and mud-cuttings transport for 80rpm and 120rpm showed deviation by a mean percentage error of 65% and 100% respectively in the initial flow rate.

Keywords: Drilling fluid velocity, Drill pipe rotation speed, Annular pressure losses, Cuttings concentration

Introduction

As depletion of light oil reservoirs occur, a tendency to produce hydrocarbon from heavy crude oil is becoming important thus a deep understanding of multiphase flow behavior in horizontal wells for system design and production is vital. High viscous oil in reservoir does not flow easily especially after primary recovery (where oil is produced as a result of natural energy of reservoir), even in high permeable reservoirs. As a result, a combination of a very high angle well path and a poor quality of reservoir might require a more complex drilling fluid specification compared to that used when drilling a conventional directional well, not only because of the increase in angle, but because poor quality reservoirs do not tolerate any further degradation (Qischeng and Yongchun, 2023).

In the last decades (beginning with development of nuclear plants), there have been a large number of research work on two-phase gas-liquid flows in the presence of singularities, - sudden contraction and

expansion (Wadle, 1989; Attou and Bolle, 1997; Chen *et al.*, 2007; Chen *et al.*, 2009). However, a limited number of research activities are dedicated to solid-liquid flow through singularities, in spite of its relevance in the petroleum industries. In order to reduce risk of operation for industrial application with respect to solid-liquid flow through singularity, the understanding of the characteristics of water or mud flow, such as distributed and pressure losses, spatial distribution of phases (Hold-up) and flow regimes is required.

Another crucial component of multiphase flow design in horizontal wells involves accurately measuring the mass flow rate of phases. Thus, multiphase measuring devices could be considered as a type of singularity. So, if multiphase behavior through abrupt change of cross-sectional area of pipe is understood, it would help in the characterization of water-mud flow through multiphase flow devices. In spite of its importance, very limited information regarding such a two-phase flow is available in the literature. Hence, it is

important to investigate the characteristics of two-phase flow because of its significant effect of the pressure losses (Murphy, 1999).

Among few investigators who made attempt to estimate pressure losses and cuttings concentration in annular geometries with or without drill pipe rotation by employing either experimental or numerical approaches are; Tomren *et al.* (1986), Sifferman *et al.* (1992), Adari *et al.* (2000), Ahmed *et al.* (2010), Ozbayoglu *et al.* (2010) and Evren *et al.* (2010). Ofei *et al.* (2013) employed CFD technique to analyze the influence of diameter ratio, fluid velocity, fluid type, fluid rheology and drill pipe rotation speed on pressure loss in eccentric horizontal wellbore with the presence of cuttings. The annular diameter ratio varied from 0.64-0.90 with the drill pipe positioned at eccentricity of 0.623, and rotating about its own axis at 80 and 120 rpm. The drilling fluids were modeled using Newtonian and Power-Law fluids. In another study, Ofei *et al.* (2014) employed the inhomogeneous (Eulerian-Eulerian) model to simulate a two-phase solid-fluid flow and predict pressure losses and cuttings concentration in eccentric horizontal annuli as a function of varying drilling parameters: fluid velocity, diameter ratio (ratio of inner pipe diameter to outer pipe diameter), inner pipe rotation speed, and fluid type. Experimental data for pressure losses and cuttings concentration from previous literature compared very well with simulation data, confirming the validity of their model. Rushd *et al.* (2017) evaluated the effects of hydrodynamic roughness along with eccentricity and rotational speed of a drill pipe. Simulations were conducted using the commercial CFD code, ANSYS CFX 16.2 and results validated using experimental data. The research showed that pressure losses are strongly dependent on the equivalent roughness of a drilling annulus, eccentricity and rotational speed of the drill pipe. Ozbayoglu *et al.* (2021) used data-driven models to address the estimation of cuttings concentration and frictional loss estimation in a well during drilling operations. The training of the models were determined using the experimental data regarding cuttings transport tests collected over years at drilling projects. It was observed that in many cases, data-driven models performed significantly better than the mechanistic model. It was also concluded that using the independent drilling variables directly as the model inputs provided more accurate results when compared with dimensional groups used as model inputs. Mao *et al.* (2023) simulated the influence of well inclination angle on cuttings transport in the whole inclined section and horizontal section. The cubic spline interpolation method was used to carry out curve fitting on the well trajectory and establish a two-layer dynamic model of cuttings transport in

long horizontal wells considering the actual well trajectory, using MATLAB for simulation. Research results demonstrated that, under drilling conditions, cuttings are difficult to deposit in the section with small deviation angle, the degree of hole cleaning increased with the flow rate and the drilling fluid density, and lower ROP is helpful in hole cleaning. The degree of hole cleaning increased with the flow rates and drilling fluid density.

Nonetheless, it is widely acknowledged that pressure losses in vertical, inclined and horizontal wells are influenced by multiple factors. Therefore, greater attention needs to be directed towards the factors that substantially impact transport efficiency in horizontal wells.

Thus, this research work investigated the effect of drilling fluid velocity and drill pipe rotation speed on annular pressure losses and cuttings concentration in horizontal wells. The inhomogeneous (Eulerian-Eulerian) model was employed to simulate the two-phase solid-fluid flow. The simulation was conducted using the work bench platform of ANSYS CFX 15.0. The focus was on evaluating the influence of varying drilling parameters: fluid velocity, drill pipe rotation and fluid type on annular pressure loss and cuttings concentration when the diameter ratio and eccentricity are constant during horizontal well drilling. Furthermore, the study explored the possibility of conducting a more in-depth investigation to determine whether a notable disparity in pressure loss exists, employing both water and mud as carrier fluids. The present investigation is limited only to turbulent flow with Reynolds number at the range $Re > 10^4$.

Modeling of the flow

In this study, the Eulerian-Eulerian model which regards both continuous and dispersed phases as continuous media, is preferred due to its ability to handle high solid volume fractions. Furthermore, it accounts for solid particle-particle interaction and includes turbulence automatically (Faeth, 1987). The flow of the incompressible fluid (Newtonian/non-Newtonian) in the annulus is described using the simplified forms of continuity and momentum equations for steady, isothermal and turbulent flow as follows.

Continuity equation

The continuity Equation (1) for the mixture is obtained through the differential method as;

$$\frac{\partial}{\partial t}(a_q \rho_q) + \nabla(a_q \rho_q U_q) = 0 \quad (1)$$

where, ρ_q is the phase reference density or the volume averaged density of the q^{th} phase in the

solution domain, U_q is the velocity vector, and a_q is the phase volume fraction (Cheng, 2002).

Momentum equation

The momentum equations for the forces acting on each phase and inter-phase are given in Equation (2) as,

For liquid phase (l)

$$\rho_l a_l \left[\frac{\partial U_l}{\partial t} + U_l \cdot \nabla U_l \right] = -a_l \nabla p + a_l \nabla \cdot \bar{\tau}_l + a_l \rho_l g + (F_l + F_{ll} + F_{vml}) \tag{2}$$

where, ρ_l is density of the liquid phase, a_l is the liquid phase volume fraction, U_l is velocity vector of the liquid phase, ∇ is the divergence, p is the pressure, $\bar{\tau}_l$ is liquid phase stress-strain tensor, g is acceleration due to gravity, F_l is liquid phase external body force, F_{ll} is liquid phase lift force and F_{vml} is liquid phase virtual mass force.

For solid phase (s), Equation (3)

$$\rho_s a_s \left[\frac{\partial U_s}{\partial t} + U_s \cdot \nabla U_s \right] = -a_s \nabla p + a_s \nabla \cdot \bar{\tau}_s + a_s \rho_s g + (F_s + F_{sl} + F_{vms}) \tag{3}$$

where, ρ_s is density of the solid phase, a_s is the solid phase volume fraction, U_s is velocity vector of the solid phase, ∇ is the divergence, p is the pressure, $\bar{\tau}_s$ is solid phase stress-strain tensor, g is acceleration due to gravity, F_s is solid phase external body force, F_{sl} is solid phase lift force and F_{vms} is solid phase virtual mass force.

Materials and Methods

In this section, the modified model for pressure loss used in this study is obtained. Cuttings feed concentration computed, and simulation setup presented. To perform the verification check, pure water and mud as carrier fluids with different velocities were simulated through the model and their annular pressure loss were recorded and validated with the prediction runs.

Pressure Loss

To estimate the pressure loss, the empirical model of pressure loss ratio (PLR) proposed by Ahmed *et al.* (2010) was adopted and modified. This empirical correlation was developed to predict the pressure loss ratio for rotating and non-rotating drill string for a single -phase flow and is given as Equation (4);

$$PLR = 0.36 \times \left(13.5 + \frac{\tau_y}{\rho v^2} \right)^{0.428} \times \varepsilon^{0.158} \times n^{0.054} \times T_a^{0.042} \times k_{Ind} \left(\frac{1}{\kappa} - 1 \right)^{-0.0152} \tag{4}$$

where, τ_y is shear stress, ε is eccentricity, ρ is density, n is flow behavior index, v is fluid velocity, T is Taylor number and κ is diameter ratio.

Considering the geometric, kinematic and dynamic similarity of Ahmed *et al* (2010) model to that studied here, Equation (4) was extended to a two phase flow as Equation (5) by incorporating,

$$R_e \times \left(\frac{R_{op} A_{bit}}{0.5 Q V_a} \times L_h \right) \tag{5}$$

Ofei *et al* (2014).

Therefore, the modified model Equation (6) used in this study is,

$$PLR = 0.36 \times \left(13.5 + \frac{\tau_y}{\rho v^2} \right)^{0.428} \times \varepsilon^{0.158} \times n^{0.054} \times T_a^{0.042} \times k_{Ind} \left(\frac{1}{\kappa} - 1 \right)^{-0.0152} \times R_e \times \left(\frac{R_{op} A_{bit}}{0.5 Q V_a} \times L_h \right) \tag{6}$$

where, R_e is Reynolds number, R_{op} is rate of penetration, A_{bit} is Area of bit, V_a is the volume of annulus, sQ is Injection velocity and L_h is the hydrodynamic length.

Flow with rotating inner pipe is known to introduce Reynolds number which was altered in Equation (4) and for an enclosed fluid system where the turbulence is fully developed the viscous forces were considered negligible, and the force of gravity and surface tension were entirely not considered.

Cuttings Concentration

The cuttings feed concentration provides insight into the quantity of particles in motion introduced to the annular space. Meanwhile, the hydrodynamic entrance length (L_h) eliminates end effects and ensures fully developed flow. The hydrodynamic length was presented by Shook and Roco (1991) as $L_h = 0.062 NRe (D)$. Yet, in the context of a non-Newtonian fluid within a two-phase flow in an annular gap, such expression has not been documented in existing literature. As a rule of thumb, we have adopted L_h by replacing the pipe diameter D with a hydraulic radius $\Delta R = R_o - R_i$.

The cuttings feed concentration was computed as a function of area of bit, injection velocity, and rate of penetration, Ozbayoglu *et al* (2010). Based on experimental findings the ratio of the particle transport velocity to the average annular fluid velocity (R_T) was taken as 0.5, Sorgun *et al* (2011).

Simulation Setup

The horizontal eccentric wellbore model was developed conforming to the test parameters

published in Osgouei (2010). Tables 1 and 2 show the parameters used in this study.

experimental data, confirming the validity of the current model setup. Thus, the predicted data is taken to be the accepted values or reference point

Table 1: Summary of experimental data from previous studies

Parameters	Values
Fluid Density (kg/m ³)	998.5
n(-)	1.0
K,(Pa s ⁿ)	0.001
Pipe rotation (rpm)	80
K(D1/D2)	0.64
ε(-)	0.623
Fluid velocity (m/s)	1.524-2.743
Avg. cuttings size (m)	0.00201
Cuttings density (kg/m ³)	2761.4
ROP (m/s)	0.00508

Table 2: Parameters used in the simulation

	Case 1	Case 2
Rheological and drilling parameter	Water	Mud
Fluid Density (kg/m ³)	998.5	1000
Cuttings density (kg/m ³)		2761.4
Avg. cuttings size (m)		0.00201
Flow behavior index, n	1.0	0.51
Viscosity consistency, K, (Pa s ⁿ)	0.001	0.044
Fluid velocity (m/s)		1.524-2.7432
Inner pipe rotation speed(rpm)		80,120
Diameter ratio (k=D1/D2)		0.64
Eccentricity (ε)		0.623
ROP (m/s)		0.00508
Well bore length(m)		0.61
Well bore Radius(m)		0.074
Drill pipe Radius(m)		0.047
Temperature		25°C (Isothermal)

Results and Discussion

In order to check the reliability of the empirical modeling methodology, taking into account the combined effect of the process variables, the prediction model was validated against experimental data available from previous studies. Pressure loss data for cuttings water flow in horizontal wellbore were adopted from Ofei et al (2014). And simulation was conducted using the workbench platform of ANSYS CFX 15.0.

Prediction Model Validation

To validate the prediction model Equation 6, experimental data was compared with the prediction model. This is displayed in Figure 1.

From Figure 1, it is observed that both data show a similar trend, though the calculated pressure loss is seen deviating slightly from the experimental data by a mean percentage error of 0.91%. It however shows a good agreement between calculated and

for this study.

Effect of Fluid Velocity

The effect of fluid velocity on annular pressure loss and cuttings concentration when diameter ratio and eccentricity are constant with drill pipe rotation speed at 80rpm was evaluated. The results are displayed in Figures 2 and 3, respectively.

From Figure 2, it is seen that when water is used as carrier fluid, increasing the fluid velocity significantly increases pressure losses. Furthermore, it is seen that pressure loss simulations is slightly higher at fluid velocity of 2.743m/s for 80rpm as compared to prediction for water flow cuttings injection.

From Figure 3, it is clearly observed that the pressure loss simulations is slightly higher at fluid velocities of 1.524m/s to 2.438m/s as compared to prediction at 80rpm for mud flow with cuttings injection. As both water and mud velocities

increase, the annular pressure loss also increases. This is in agreement with previous researches, where it was found that fluid velocity is a dominant factor during cuttings transport.

eccentricity are constant, using both water and mud as carrier fluids is depicted in Figures 4 and 5, respectively.

In Figure 4, the deviation from ANSYS simulation

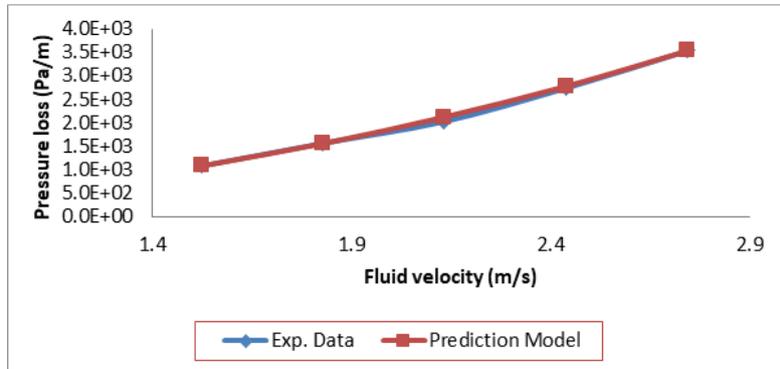


Figure 1: Experimental and prediction data comparison for pressure loss for cuttings water flow at 80 rpm

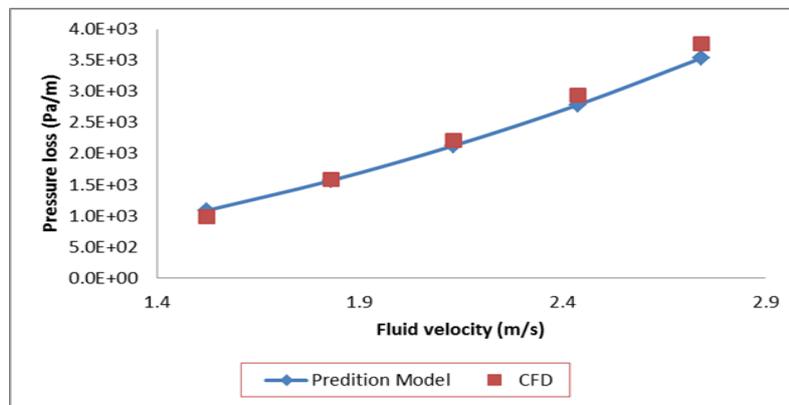


Figure 2: Comparison of Annular pressure loss between ANSYS simulations and prediction for drill pipe rotation speed at 80rpm for water-cuttings transport

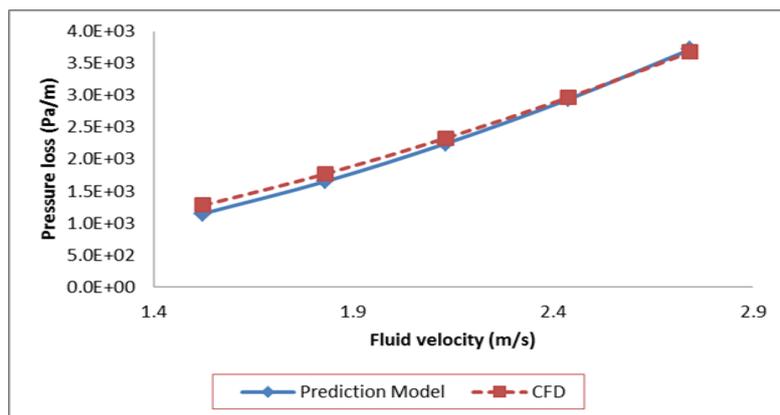


Figure 3: Comparison of Annular pressure loss between ANSYS simulations and prediction for drill pipe rotation speed at 80rpm for mud-cuttings transport

Effect of Drill Pipe Rotation Speed and Fluid Type

The effect of increasing drill pipe rotation speed on annular pressure loss when diameter ratio and

results for water and mud at 80rpm was small with a mean percentage error of 9%.

From Figure 5, it is seen that the deviation from ANSYS simulations results for water and mud at

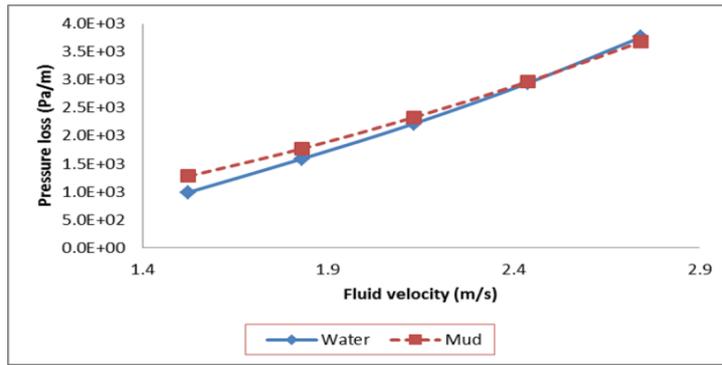


Figure 4: Comparison of Annular pressure loss between ANS simulations for water and mud-cuttings transport with drill pipe rotation speed at 80rpm

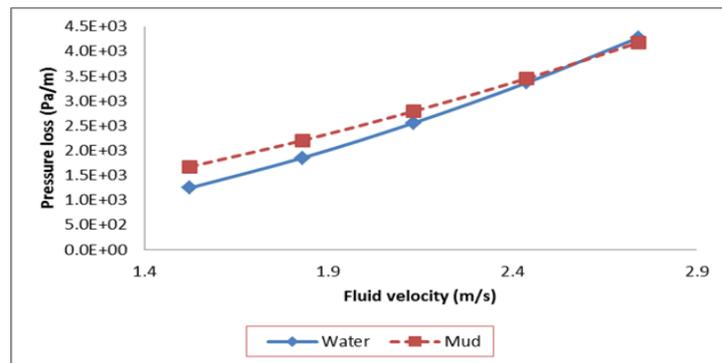


Figure 5: Comparison of Annular pressure loss between ANSYS simulations for water and mud-cuttings transport with drill pipe rotation speed at 120rpm

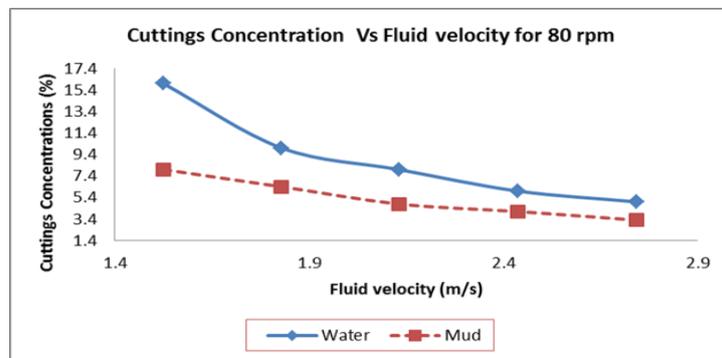


Figure 6: Comparison of Cuttings concentration between ANSYS

120rpm was also very little with a mean percentage error of 13%.

Cuttings Concentration

In Figures 6 and 7, it is seen that the cuttings concentration is highest with 16% when the annular velocity is at the lowest reading 1.524m/s for both water and mud-cuttings transport at 80rpm and 120rpm respectively. It is noted that as the water velocity increases, the cuttings concentration decreases significantly. This is in agreement with

existing studies, because low water velocity is unable to prevent the cuttings from slipping downward as their slip velocity is higher.

From Figure 6, it could be observed that the water velocity has not reached the required minimum transport velocity (MTV). As a result, cuttings particles settled at the bottom of the annulus and eventually a continuous stationary cuttings bed was formed. As the flow rate increased, the transport velocity exceeded the required MTV. Consequently, the cuttings were conveyed through

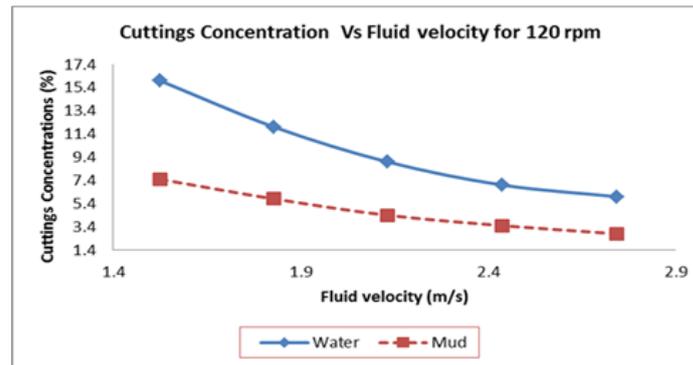


Figure 7: Comparison of Cuttings concentration between ANSYS simulations for water and mud-cuttings transport for 120rpm

two distinct mechanisms; namely, rolling and saltating on the well's bottom wall, and dispersion within the suspended water.

It is noticed that increasing the drill pipe rotation at high fluid velocity did not result in any significant reduction in cuttings concentration. It is further observed from Figures 6 and 7 that the results show deviation by a mean percentage error of 65% and 100% respectively in the initial flow rate. However, as the flow rate increased, the readings from both simulations converged.

Detailed Cutting Particle Movement Analysis

The contours of rotating inner pipe at rotational speed of 80rpm were obtained at the lowest velocities 1.524m/s and highest 2.743m/s. Also obtained at rotational speed of 80rpm were the 3D streamlines of cuttings at velocities 1.524m/s and 2.743m/s respectively.

Conclusion

The effect of drilling parameters on drilling performance factors in horizontal wells using simulation approach was studied in this paper. The focus was on evaluating the influence of fluid velocity, drill pipe rotation and fluid type on annular pressure loss and cuttings concentration when the diameter ratio and eccentricity are constant during horizontal well drilling. Results showed that at 80rpm, pressure loss simulations were slightly higher at fluid velocity of 2.743m/s as compared to prediction for water flow cuttings injection. Also, at fluid velocities of 1.524m/s to 2.438m/s pressure loss simulations were seen slightly higher as compared to prediction for mud flow with cuttings injection. As both water and mud velocities increased, the annular pressure loss also increased with mean percentage error of 9% and 13% deviation from ANSYS simulation for water and mud-cuttings transport respectively. It was observed that the cuttings concentration was highest with 16% when the annular velocity was at the lowest reading 1.524m/s for both water and mud-cuttings transport at 80rpm and 120rpm

respectively. The influence of increasing drill pipe rotation speed for water-cuttings transport from 80 rpm to 120 rpm had a negative impact where the cuttings concentration was observed to increase. To explain this behavior, the low viscous water had generated a high turbulence as a function of both axial and rotational flows, which in addition to gravity could cause rapid settling of cuttings in the annulus. In addition, the drill pipe rotation at 80rpm and 120rpm reduced the cuttings concentration by sweeping it into the fluid domain at the wide gap where the velocity was high enough to carry the cuttings back to the surface. The comparison of cuttings concentration between ANSYS simulations for water and mud-cuttings transport for 80rpm and 120rpm showed deviation by a mean percentage error of 65% and 100% respectively in the initial flow rate. However, as the flow rate increased, the readings from both simulations converged. The detailed cutting particle movement analysis was conducted and the following were observed: The contours of rotating inner pipe at rotational speeds of 80 rpm were obtained respectively at velocities 1.524 m/s and 2.743 m/s. Also obtained at rotational speed of 80rpm were the 3D streamlines of cuttings velocity at velocities 1.524 m/s and 2.743 m/s respectively. The 3D velocity vectors of cuttings at velocities 1.524 m/s and 2.743 m/s were also obtained.

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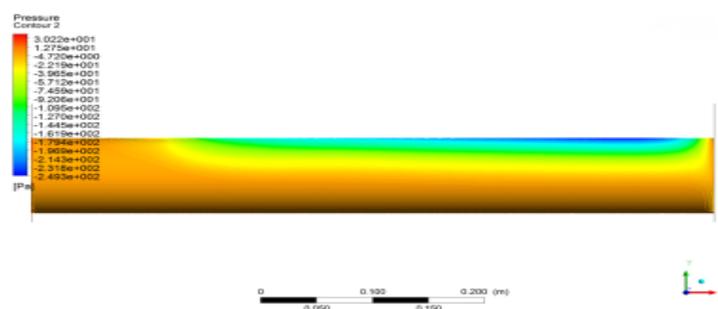


Figure 8(a): Contours of rotating inner pipe at rotational speed of 80rpm at velocity 1.524m/s

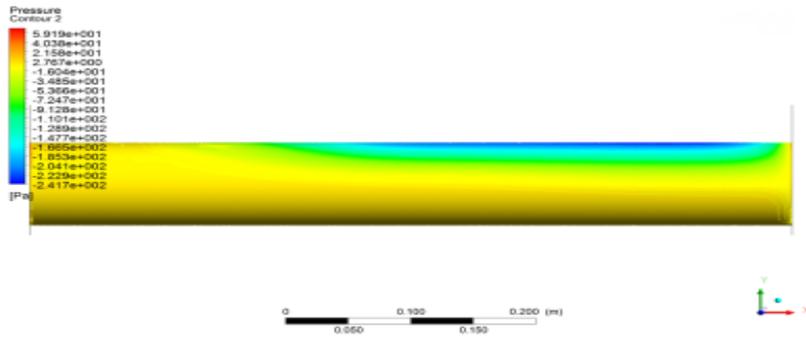


Figure 8(b): Contours of rotating inner pipe at rotational speed of 80rpm at velocity 2.743m/s

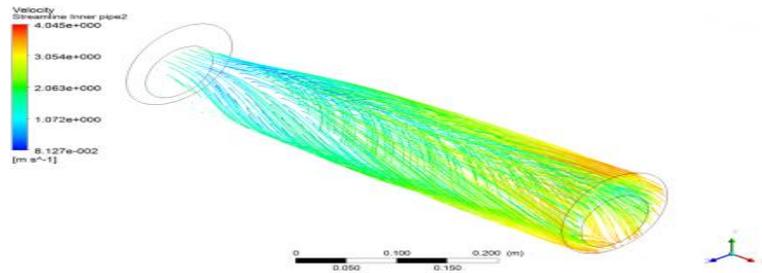


Figure 8(c): 3D streamlines of cuttings velocity at velocity 1.524 at rotational speed of 80rpm

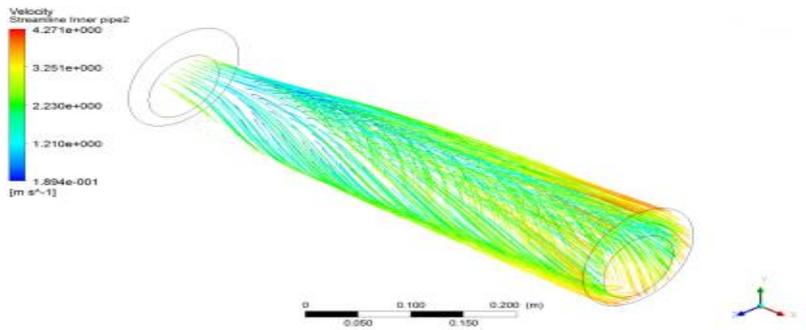


Figure 8(d): 3D streamlines of cuttings velocity at velocity 2.743 at rotational speed of 80rpm

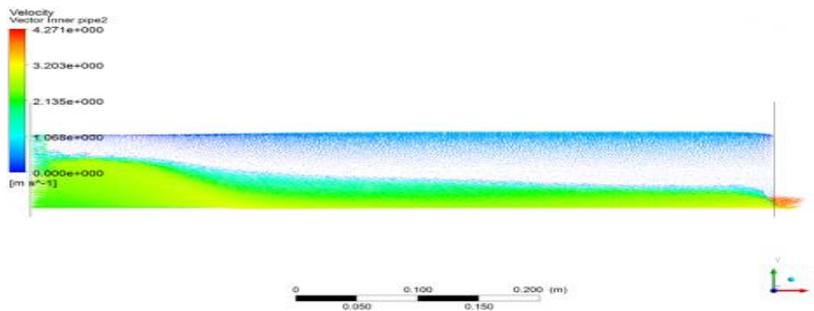


Figure 8(e): 3D velocity vectors of cuttings at velocity 2.743 rotational speed of 80 rpm