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DRILL PIPE INCLINATION EFFECTS ON HORIZONTAL WELLS CLEANING PROCESS

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Abstract. *Horizontal wells are very common in the petroleum industry due to the increase of the wellbore contact area with the reservoir. However, the drilling process is complex and many aspects can affect its performance. Among them, it is possible to quote the drilling fluid, the axial flow, the rotational speed, eccentricity and inclination of the drilling pipe. This work uses Computational Fluid Dynamics (CFD) to evaluate the effect of the drill pipe inclination on the drilling process performance. The drilling fluid is represented by the power law rheological model with consistency index K = 0.678 and power index n = 0.27. The annular region is 4.9 m long and the inner and outer cylinder diameters are 0.058 m and 0.104 m, respectively. A concentric configuration was used as reference and one side of the drill pipe was displaced in order to promote the inclination of the drilling column, which varied from 0 to 0.004 m/m. For the concentric configuration, the effective viscosity was very small near the walls due to the large shear strain. However, in the central region of the annulus, it increased considerably (μe = 1.2 Pa.s), which is important to carry the cuttings away. For the inclined configuration, the increase in the angle formed by the drilling column with the horizontal plane, changes the flow pattern and decrease the effective viscosity, decreasing the cuttings transport capacity. For the fluid considered, the inclination of the drilling string did not affect the pressure drop due to the small values of shear strain near the walls.*

Keywords: *CFD, non-Newtonian, horizontal wells.*

1. INTRODUCTION

The horizontal drilling technique has been widely used in the petroleum industry due to the increased contact area with the reservoir. However, a number of operational problems are generated from this technique. Among the parameters that affect the well cleaning process it is possible to quote: the rotational speed of the drill string, the size and density of the gravel particles, the eccentricity of the column, the rheology of the drilling fluid and the axial flow rate (Loureiro and Siqueira, 2006). In the literature, several authors studied the effects of these parameters on the performance of the drilling process.

One of the main problems of the horizontal drilling process is the displacement of the drill string, due to gravitational effects, which generates an eccentricity of the drill pipe in relation to the wellbore and the sedimentation of the gravel particles, forming a solid bed and impairing the transport of the cuttings outwards from the wellbore. Besides the eccentricity of the annular, the effect of gravity may also cause an inclination of the drill string, which can harm the well bore cleaning process. This inclination is generated due to the own weight of the drill pipe, which tends to move to the bottom of the well as the distance from the drill increases.

Adopting a Newtonian fluid model, Sun et al. (2014) evaluated the influence of the inclination of the well and the rotational speed of the drill string, for different flow rates, on the pressure drop and distribution of gravel in the annulus, noting that the cuttings distribution is more asymmetrical for higher rotational velocities. They also noted the existence of a critical speed above which this effect is no more significant.

Loureiro and Siqueira (2006) estimated the minimum shear stress necessary to initiate the process of erosion of a sediment bed. The authors found that the necessary shear stress, which depends on the flow rate, is directly proportional to the average size of the particles.

Taylor (1923) studied the "Stability of a Viscous Liquid Contained between Two Rotating Cylinders". The experiment he carried out consisted of two concentric cylinders filled with a fluid between them. He shows that as the inner cylinder rotates, a shear flow is established and at a critical value of Reynolds number, the flow becomes unstable, and a secondary stationary state which is characterized by toroidal vortices with axial symmetry appears. These vortices are known as Taylor vortices. As stated by him, and no doubt it is a true statement, the most successful feature of the analysis contained in his work is the accuracy with which it predicts the critical speeds at which instability appears.

Costa et al. (2013) observed the formation of Taylor vortices in the main flow on rotational speeds above 400 rpm. The formation of these vortices significantly increases the shear stress on the walls of the column, increasing the torque necessary to rotate the drill string.

Loureiro et al. (2006) evaluated the influence of the drill string rotation on the development of a sediment bed and particulate suspension. The authors evaluated various bed heights and concluded that, for higher heights, the rotation of the column affects the particle suspension due to the increased compactation process presented in this case. For lower bed heights, the rotation has displaced the particles in the direction of the inner cylinder rotation and it may aid to the transport of sediment by the axial flow.

Escudier et al. (2000) evaluated the influence of the drill string rotation on the laminar flow through an eccentric annulus and noted a strong influence of the tangential velocity on the axial velocity distribution. In addition, for eccentricity values above 0.9 and fixed Reynolds number, the increase of the drill string rotational speed provides an increased friction coefficient.

According to Pereira et al. (2010), drilling fluids, in general, are suspensions with non-Newtonian rheological behavior, and may be pseudoplastic or viscoplastic. The viscoplastic suspensions are used to minimize the cuttings sedimentation when there is an interruption of fluid flow. In the case of non-Newtonian fluids, some studies are available in the literature.

Vieira Neto et al. (2014) analyzed the influence of the inner cylinder rotation in the hydrodynamic behavior of the annular space through experimental and CFD results for eccentric and concentric configurations. The authors have noted an increase in the pressure drop along the well in the eccentric configuration as inner cylinder rotation increases. Furthermore, they found the existence of preferential flow zones and flow stagnation regions in the annulus.

Ofei et al. (2014) evaluated the effects of the diameter ratio, flow rate, column rotation and type of fluid on the pressure drop and particles concentration in an annular region. The results showed that higher diameter ratios, especially above 0.8, cause higher pressure losses, but reduces the concentration of particles in the annular. The authors also found that the most significant factor for the transport of cuttings is the fluid flow rate, however, this effect decreases dramatically as the diameter ratio is increased.

Nouri and Whitelaw (1997) conducted experimental studies to evaluate the effect of the inner cylinder rotation for Newtonian fluids and non-Newtonian fluids and found that the rotation velocity of the inner cylinder used in their experiments has similar effects on both types of fluids, having increased by more than 30% the resistance to the fluid flow at low Reynolds numbers. In addition, the increased rotation had a strong influence on the velocity components in the lower annulus region.

Escudier et al. (2002b) performed experimental and numerical studies for the flow of non-Newtonian fluids, comparing the velocity profiles with results of other studies in the literature. According to the results obtained by the authors, the pressure gradient decreases with the increase of the rotational speed, which is justified by the influence of rheological characteristics of the fluid and the predominantly axial flow.

Loureiro (2004) performed experimental and numerical studies for the flow in an annular space partially obstructed using a plate placed between concentric cylinders. The results showed that the flow obstruction delay the transition to the Taylor vortices regime, especially for Newtonian fluids. For the non-Newtonian fluids, the author concluded that the presence of obstruction plate had little interference in the flow, in the region near the outer cylinder, due to shear-thinning fluid effects.

Pereira et al. (2007) evaluated the effects of viscosity, eccentricity, flow rate and drill string rotation on the axial and tangential velocity profiles and also on the pressure loss in the annulus. As a result, the fluid flow rate was the operational variable with the greatest influence on the pressure drop and the eccentric configuration had lower losses compared to the concentric case. In addition, to the concentric case, the effect of the rotation does not influence significantly the friction losses, whereas for the eccentric case, greater losses were observed when the rotating column is present.

Most published studies evaluates the flow of non-Newtonian fluids in the annular space, concentric and eccentric, with or without rotation of the inner cylinder, but for cases in which there is no variation in the column position along the axial direction. This study aims to evaluate the influence of the inclination of the drill string on the dynamics of fluid flow in the annulus through the CFD technique.

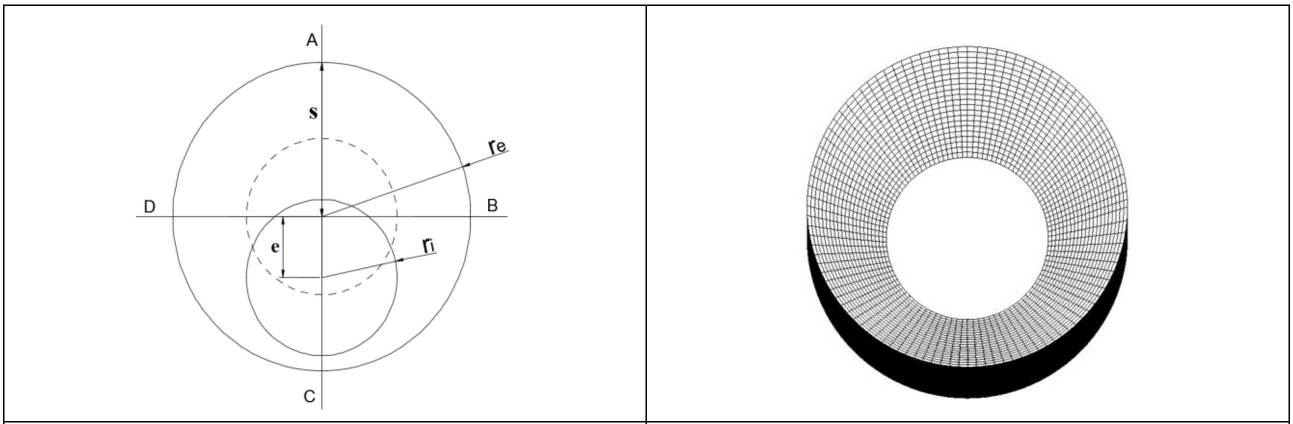
2. METODOLOGY

2.1. Geometry

The flow problem was investigated using the simplification of an annular space formed between the well and the drill string with the inner cylinder inclination. The geometry parameters were defined based on the experimental model of Escudier et al. (2002a), only the length of the section was changed for computational cost reduction purposes. The entrance region of the flow was maintained with the centralized inner cylinder to represent the concentricity of the system at this location, since the drill presence ensures the centering of the drill column. In the outlet zone, the column was moved to the lower region of the well, in order to provide the desired inclination.

The schematic representation of the studied geometry is shown in Fig. 1(a). The geometry consists of an annular space formed by two tubes of 4.9 m length (L) with inner cylinder radius (r_i) equals 0.0254 m and outer cylinder radius (r_e) equals 0.0502 m. The letters A, B, C and D are sectors of the annular space used to determine the velocity and viscosity profiles.

The study was carried out using the Computational Fluid Dynamics technique (CFD) with the commercial software Ansys® CFX - Version 16.0 Preview 4.



(a) Geometry | (b) Computational grid

Figure 1 – Schematic representation of the geometry evaluated in this study.

A bi-dimensional mesh in the rz plane was used to discretize the computational domain in the annular space. The mesh features 21 divisions in the radial direction and the number of divisions in the axial and tangential directions is automatically controlled by the software, creating a total of 5,093,088 grid elements for all cases. In addition, they used only hexahedral cells, configuring a structured mesh condition. The mesh used can be seen in Fig. 1(b) for the 0.002 m/m inclination case.

2.2. Governing Equations

The equations governing the flow for the cases analyzed in this paper are the continuity and the Navier-Stokes equations, described by Eq. (1) and (2), respectively.

$$\nabla.\vec{V} = 0 \quad (1)$$

$$\rho\frac{D\vec{V}}{Dt} = -\nabla P + \rho g + \mu(\nabla^2\vec{V}) \quad (2)$$

In the above equations, V is velocity, ρ is specific mass, P is pressure, g is gravity and μ is the effective viscosity of the fluid.

For the case of non-Newtonian fluids, the dynamic viscosity is replaced by the effective viscosity (μ_e), determined by chosen rheological model and an expression for the characteristic shear strain (Pereira et al., 2006).

2.3. Physical properties of the fluid

The rheological model selected to represent the viscosity of the non-Newtonian fluid was the Power-law, which is given by Eq. (3).

$$\mu_e(\dot{\gamma}) = k\dot{\gamma}^{n-1} \quad (3)$$

In the above equation, μ_e is the effective viscosity, $\dot{\gamma}$ is the deformation rate, k is the consistency index and n is the Power-law fluid behavior index.

The rheological data were selected following the work of Vieira Neto (2014) for a Xanthan gum (XG) solution of 0.2 % concentration. The rheological parameters of the fluid are shown in Tab. 1.

The density of the solution was considered equal to the density of water (998 kg/m³) since the concentration of XG is low enough not to promote significant changes in their density.

Table 1 – Fluid rheological parameters for the Power-law model.

Fluid	**Rheological Parameters**	
	$k\ (Pa.s^{-1})$	$n\ (-)$
0.2% XG Solution	0.678	0.27

2.4. Dimensionless parameters

Some dimensionless parameters are used to assist the comparison with results found in literature. The inclination ($I = e/L$) indicates the level of radial displacement of the inner cylinder (e) in relation to the length of the analyzed section (L); The dimensionless axial velocity ($U_{adim} = V_Z/V_m$) is the ratio between the local axial velocity (V_z) and the bulk mean flow velocity (V_m); The dimensionless tangential velocity ($V_{adim} = V_\theta / \omega r_i$) is the ratio between the local tangential velocity (V_θ) and the inner cylinder tangential velocity (ωr_i), where ω is the inner cylinder rotational speed; and the dimensionless position in the gap ($S_{adim} = (r - r_i)/S$) indicates the radial positioning of the evaluated parameter in the annular gap between the inner and outer cylinders. For each sector, S varies along the longitudinal axis and represents the distance between the drill string and the outer wall in the sector.

Another important dimensionless parameter is the Reynolds number (Re_{MR}), Eq. (3), which is a parameter used to characterize the flow regime. According to Pereira (2006), generally, the end of the laminar regime is considered to occur for Re_{MR} in the range of 2000-2500.

$$Re_{MR} = \frac{\rho v^{(2-n)} D_H^n}{k} \tag{3}$$

In the above equation, D_H represents the Hydraulic diameter.

2.5. Simulation parameters

The critical Reynolds number that ensures laminar flow condition was determined following the proposal of Rayan and Johnson (1959 cited Pereira, 2006), which provides the transition Reynolds number as a function of the power-law fluid behavior index.

$$(Re_{MR})_C = \frac{6464n}{(3n+1)^2}(2+n)^{(2+n)(1+n)} \tag{4}$$

The critical Reynolds number, determined from Eq. (4), was used in Eq. (3) to set the maximum flow rate for the laminar flow condition.

For the numerical simulation, the gravity effects were not considered, since the flow is modeled as a single phase. The flow regime is defined as laminar, the coordinate axis was set at the origin of the internal cylinder and the convergence criterion adopted was 10^{-4} maximum residual for all parameters.

In order to evaluate the effects of the inclination of the drill string on the laminar flow behavior, five conditions were simulated numerically. Five inclination values were analyzed varying of 0 to 0.004 m/m. In all cases, the inner cylinder rotation was set to 20.94 s^{-1} and the flow rate set to 0.010 m^3/s.

3. RESULTS

In this section, the results are presented in two parts: the first shows the validation of the proposed model and the second presents the results for the non-Newtonian fluid flow field in the annulus with the inner cylinder inclination. The effective viscosity, axial and tangential velocity profiles and the axial velocity contours are shown for the cases analyzed.

3.1. Computational model validation

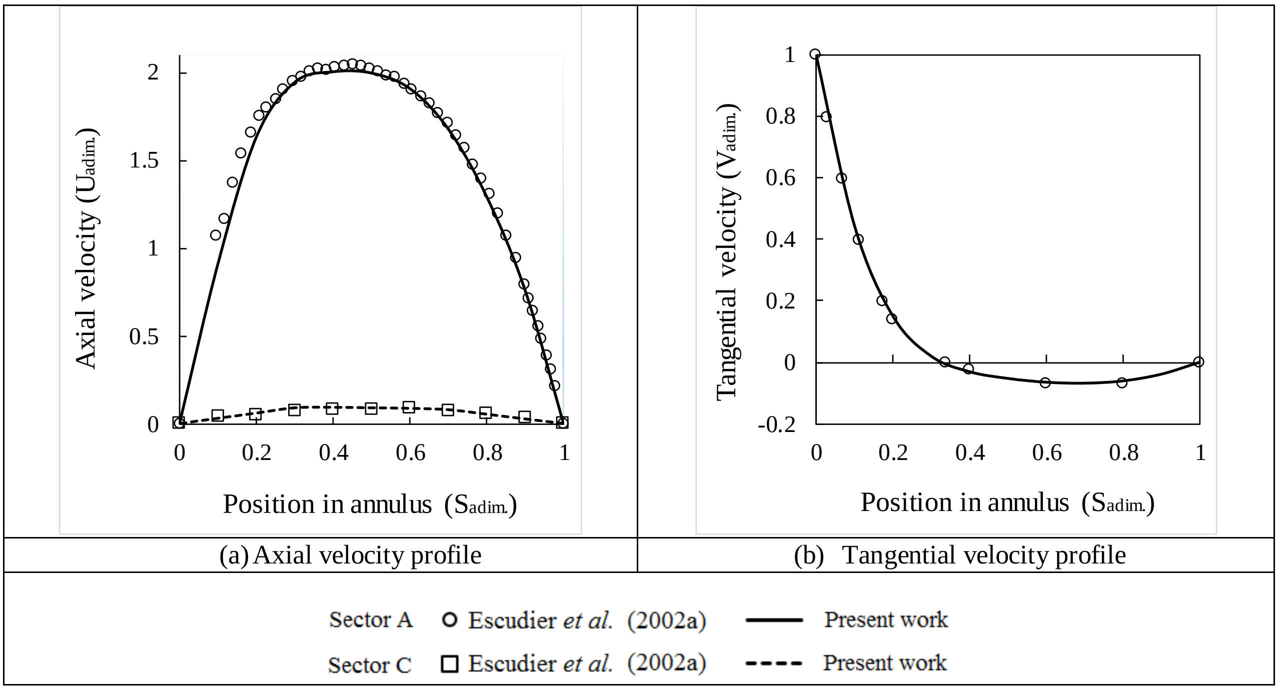
A set of simulations was performed following the work of Escudier et al. (2002a) for validation of CFD technique. The configuration evaluated the laminar flow of non-Newtonian fluid through an eccentric annular space (ε = 0.8), using the Cross rheological model. The conditions used in the simulations are presented in Tab. 2.

Table 2 – Operational and flow parameters for validation simulation.

$U\ (m/s)$	$\omega\ (s^{-1})$	$\mu_0\ (Pa.s)$	$K_{CR}\ (s^n)$	n_{CR}
0.268	5.35	0.177	0.63	0.551
	5.24	0.262	2.414	0.504

Figure 2 shows the comparison between the experimental results obtained by Escudier et al. (2002a) and the numerical results obtained in this work for axial and tangential velocity profiles in the higher and lower positions at the annular space of the analyzed section. The dimensionless axial (U_{adim}) and tangential (V_{adim}) velocity profiles were plotted as a function of dimensionless position in the gap.

The data presented in Fig. 2 shows good agreement between the results obtained in this study and the results obtained by Escudier et al. (2002a), validating the model used for the simulations. As depicted in Fig. 2(a) the flow in the lower gap is almost stagnated and the flow occurs basically in the upper gap due to the resistance impaired by the larger space for the fluid to flow. The negative velocities in Figure 2(b) indicates the occurrence of a recirculation zone in the upper gap (Sector A), which is caused by the rotation of the inner cylinder and the resistance caused by the lower gap to the passage of the fluid. This "counter-flow" can add to the cuttings suspension, which is benefic to the cleaning process.



(a) Axial velocity profile

(b) Tangential velocity profile

Figure 2 – Dimensionless axial and tangential velocity profiles.

3.2. Influence of the inner cylinder inclination on flow field.

The data presented in this section were evaluated at a distance of 2.5, 3.5 and 4.5 meters from the flow inlet section. Fig. 3 shows the dimensionless axial velocity profiles for the three positions described above. Data for the inclinations of 0.001 m/m and 0.003 m/m were removed to facilitate the presentation of the profiles, since they do not show significant differences from the data presented herein.

As shown in Fig. 3, the simulated profiles were found to have a flattened shape in the central region of the annular space. This behavior highlights the characteristic of a pseudoplastic fluid and is in accordance with the results obtained by Vieira Neto (2011). It is possible to note that the increase in inclination of the drill string causes the displacement of the axial flow in the direction of the wider gap. Also, for larger distances from the inlet, the flow rate in the larger annular region is higher. This behavior can be explained by the gradual reduction of the annular space in the C sector, resulting in greater restriction of fluid flow. Therefore, as it moves away from the flow inlet region, it is possible to note a worse distribution of the axial flow in the annular space, which may cause flow stagnation zones seriously impairing the transport of cuttings away from the well.

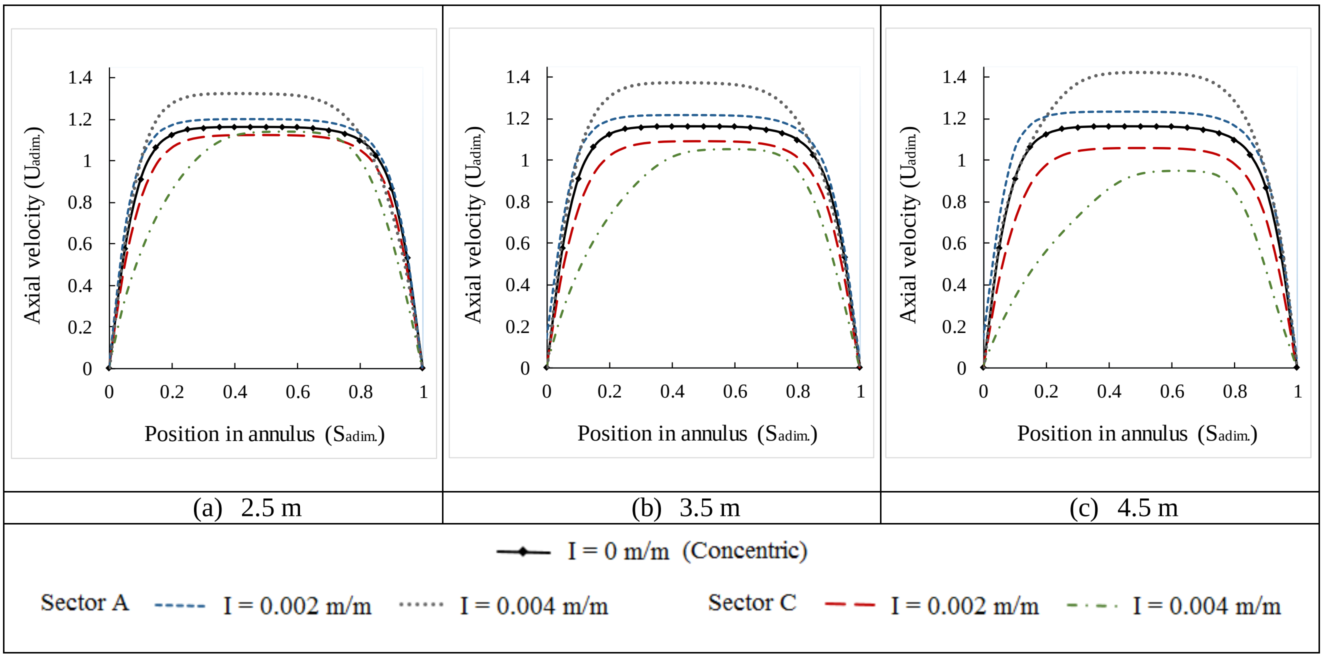
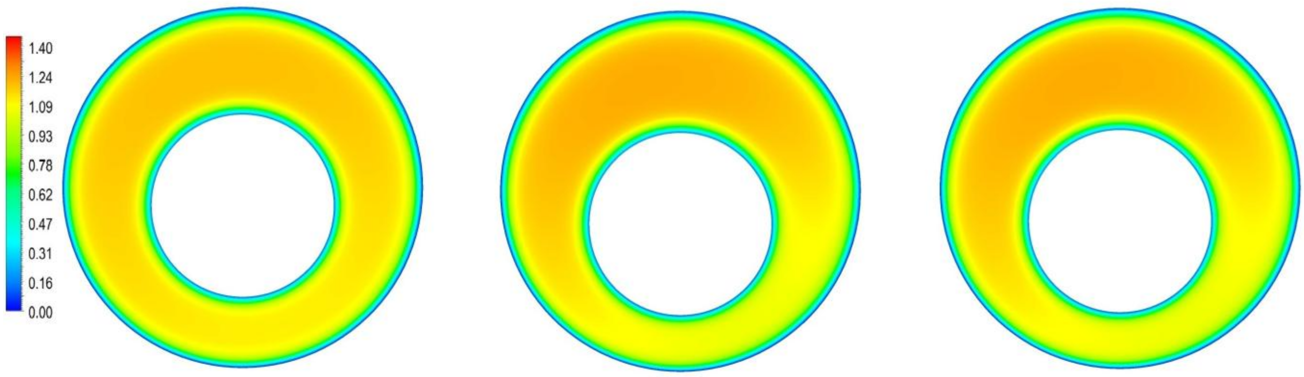


Figure 3 – Dimensionless axial velocity profiles.

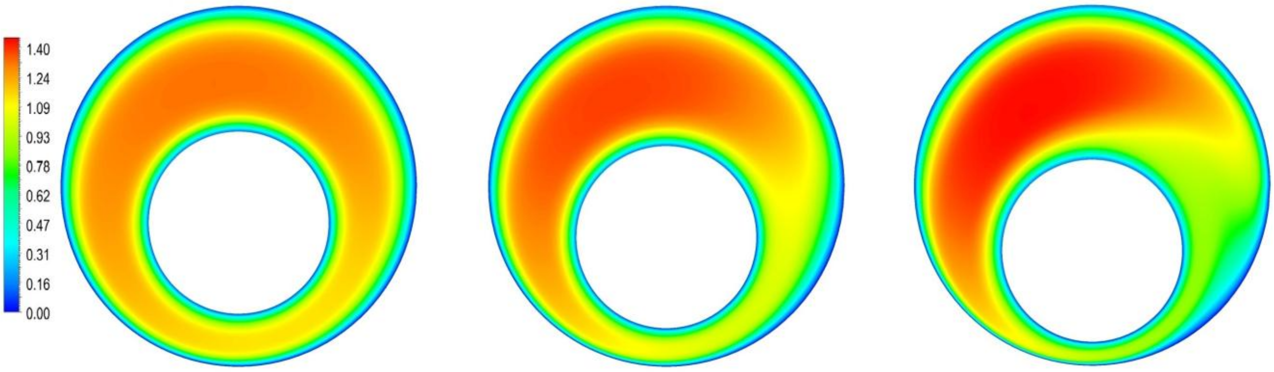
Figures 4 and 5 show the contours of dimensionless axial velocity for the inclinations of 0.002 m/m and 0.004 m/m, at the three analyzed positions (2.5 m; 3.5 m and 4.5 m). It is possible to note that, due to the drill string inclination, as the fluid moves away from the inlet section, there is an increase in fluid flow rate in the upper region of the annular space (sector A) and a consequent reduction in the lower region (sector C). As the distance from the inlet section increases, the flow rate is displaced to the larger annular gap area and this effect is more pronounced for larger inclinations of the inner cylinder. As mentioned before, this effect is explained by the increase in the resistance to the flow in the lower gap due to the proximity of the walls. This behavior was also observed for the eccentric configurations analyzed by Pereira (2007).

Still referring to Figs. 4 and 5, the increment of the inner cylinder inclination also caused greater displacement of axial flow rate in the direction of rotation, causing a worse distribution of velocities within the annular space. The higher inclination approaches the rotating cylinder to the external walls augmenting the tangential momentum transport. The bad distribution of velocities can be detrimental to the drilling process due to the possible formation of stagnant flow zones, which do not have the capacity of transport the cuttings, causing serious problems to the process.



(a) 2.5 m (b) 3.5 m (c) 4.5 m

Figure 4 – Axial velocity contours for I = 0.002 m/m.



(a) 2.5 m (b) 3.5 m (c) 4.5 m

Figure 5 – Axial velocity contours for I = 0.004 m/m.

Figure 6 shows the simulated dimensionless tangential velocity profiles for the same positions and inclinations described above. For the inclinations of 0.002 m/m, only little differences can be observed in the behavior of the tangential velocity profiles. The largest differences were observed for the case of greatest inclination (0.004 m/m), where is possible observe the presence of tangential flow still very close to the wall of the outer cylinder (S_{adim} = 1), while, for cases of lower inclinations, the tangential velocity decays quite fast, and there is virtually no tangential flow from the central region of the annular space to the wall of the outer cylinder. The accentuated increase in the tangential velocity in Sector C, for the I = 0.004 m/m inclination, is due to the very small gap formed in this section, which makes the tangential momentum exchange in this region to achieve the outer cylinder walls.

Fig. 7 shows the viscosity profiles for the same positions described above. The concentric case results are also shown for comparison. The increase of the inner cylinder inclination decreases the maximum viscosity in both annulus region. This fact is explained by the increase in the velocity gradients with the increase in the column inclination that, for the pseudoplastic fluid (shear thinning effect), decreases the effective viscosity. The distance from the entrance section also caused the same maximum viscosity reducing effect. However, this effect is less pronounced. It is also observed that for larger values of inclination, it occurs a slight displacement of the peak viscosity toward the wall of the outer cylinder. This effect can be explained by the presence of rotation of the inner cylinder.

The features of the viscosity profile presented in Fig. 7 is interesting for the drilling process because the higher viscosity values in central annular space and low values near the inner and outer walls provide the transport capacity to carry the cuttings easily, due to the increased viscosity in the central region, and causes less friction losses along the walls of the well and the drill string. Even though it does not significantly interfere in the viscosity near the walls. It is possible to note that the increase of the inclination reduces the maximum viscosity value in the central region of the annular, becoming prejudicial to the drilling process, since it reduces the cuttings transport capability.

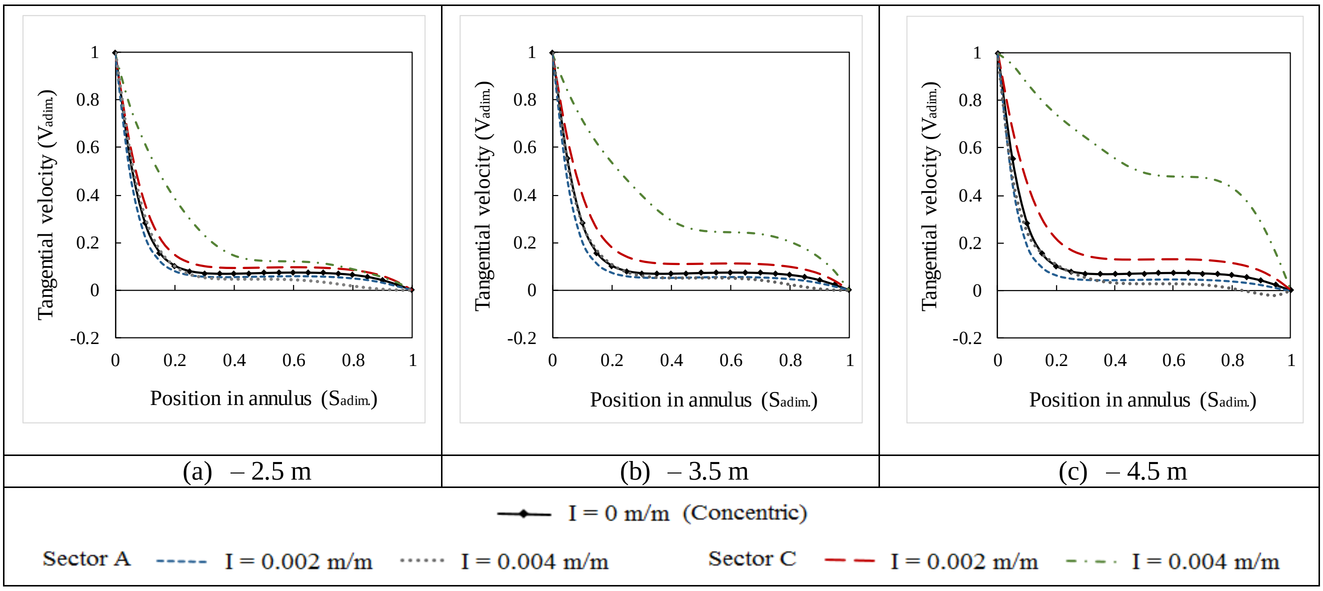


Figure 6 – Dimensionless tangential velocity profiles.

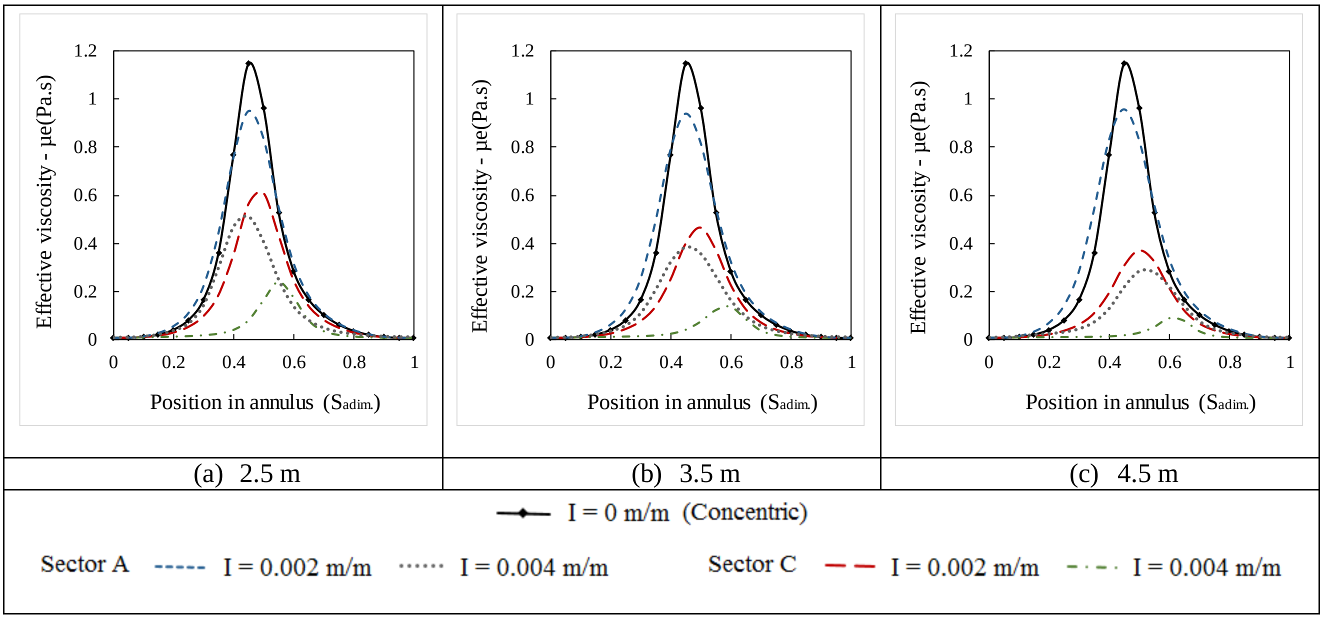


Figure 7 – Effective viscosity profiles along the well.

4. CONCLUSIONS

This study evaluated the influence of the inclination of the drill string on flow characteristics in an annular space with the inner cylinder rotation. The results showed that the increase of the drill pipe inclination promotes an uneven distribution of the flow and a reduced viscosity of the fluid in the central region of the annular space. These effects are detrimental for the drilling process because they reduce the cuttings transport capability. Although the inclination of the column has negative effects concerning axial flow, the presence of higher tangential velocities in the sector C provides an increased capacity of cuttings transport, which benefits the well cleaning process. The results presented in this work permitted a better understanding of the fluid flow behavior, allowing the identification of harmful conditions for carrying of cuttings during the drilling process of a horizontal well.

5. ACKNOLEDGEMENTS

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