DRILL PIPE ECCENTRICITY EFFECTS ON HORIZONTAL WELLS CLEANING PROCESS

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Abstract. *The horizontal drilling process is attractive due to the increase of the contact area of the wellbore with the reservoir, causing an improvement on the production and process efficiency. The horizontal drilling process is characterized by fluid flow through an annulus and, due to gravitational effects, the drillstring is usually displaced, generating an eccentric configuration which changes the flow pattern and affects the wellbore cleaning process. This study uses computational fluid dynamics (CFD) in order to evaluate the eccentricity effects on the performance of the cleaning process. The geometry consists of two cylinders, and the inner cylinder rotates with a constant speed. The bulk axial velocity was also kept constant. The drilling fluid used was an aqueous solution of 0.1% xanthan-gum/0.1% carboxymethylcellulose and the non-Newtonian characteristics of the fluid was represented by the rheological Cross model. Five eccentricity values were evaluated. The study shows that the increase in eccentricity causes a decrease of 93% in the maximum axial velocity in the narrowest gap, which would induce negative effects on the cuttings suspension process. However, this effect is compensated by the tangential velocity, which increased in this sector, improving the wellbore cleaning process efficiency. The study also shows that the increase in eccentricity lead to a decrease of 32% in the pressure drop for the case of $\varepsilon = 0.8$, for small eccentricities ($\varepsilon \leq 0.4$) the pressure drop reduction was small compared to the concentric case. Finally, an increase of eccentricity also reduces the viscosity at the narrowest gap, what could be prejudicial to the cleaning process.*

Keywords: *CFD, Eccentric annuli, Non-Newtonian fluid, Horizontal well, Wellbore cleaning*

1. INTRODUCTION

The horizontal drilling is an attractive process, owing to the increase of the contact area of the wellbore with the reservoir, causing an improvement on production and process efficiency.

The drilling process is characterized by a fluid flow through an annulus and, due to gravitational effects, the drillstring is usually displaced generating an eccentric configuration which changes the flow pattern and affects the wellbore cleaning process.

Beside the eccentricity of the drillstring, an important issue in horizontal wells drilling is the transport of the cuttings by the drilling fluid, which have a natural tendency to form a bed by the deposition of cuttings on the bottom of the annular section.

Drilling fluids are a complex mixtures of liquids, chemical products, and solids in order to maintain the stability of the wellbore, cool and clean the bit, prevent the inflow of fluids from wellbore and lubricate the drillstring. Despite these and many other functions of the fluid, the main function is the cuttings removal and, as reported in the literature, the cuttings transport is affected by many parameters, including drill pipe eccentricity, which has a great importance in the process (Caenn and Chillingar, 1996; Loureiro and Siqueira, 2006; Sun *et al.*, 2014; Tardy and Bittleston, 2015; Vieira Neto *et al.*, 2014; Pereira *et al.*, 2007).

Escudier *et al.* (2002a) carried out an experimental and numerical analysis of a fully developed laminar flow of non-Newtonian fluids through annuli, where they investigated the influence of eccentricity and inner rotation in the axial and tangential velocities. They compared their experiments with literature data and obtained a good agreement, finding similar magnitude and extension of recirculation zone and a distortion of the axial velocity field created by the combined effects of eccentricity and inner cylinder rotation.

Fang *et al.* (1999), in a numerical study, showed a bad distribution of flow pattern in the annulus, due to the effects of geometry and fluid rheology, with a tendency of stagnated flow in the narrowest section, which can prejudicial to cutting transport.

Li *et al.* (2013), in a numerical study, evaluated the flow of non-Newtonian fluids in eccentric annuli and showed the influence of eccentricity on flow pattern and axial velocity. They concluded that the greater is eccentricity, greater is the difference between the axial velocity in the wide and narrow gap.

Ogugbue and Shash (2012), in a numerical study, investigated the effect of eccentricity and diameter ratios on axial velocity and viscosity profiles. They found that, for an eccentric annulus, the velocity changes considerably and a significant reduction of velocity is observed at the narrowest gap. The opposite effect is observed at the widest gap. In addition, they concluded that the narrowest region of the annulus presents a zone of high shear, which is accompanied by a reduction in viscosity.

Pereira *et al.* (2006), in a study using computational fluid dynamic (CFD), investigated the flow pattern of viscoplastic fluids in annular space and analyzed the pressure drop and velocity profiles. They conclude that the eccentricity reduces the pressure drop in the annular space.

Siqueira *et al.* (2014), using CFD technique, analyzed the influence of axial flow and eccentricity rate on the performance of the cleaning process in an eccentric wellbore with rotation of the inner cylinder, and concluded that the increase in eccentricity rate also affect the flow and leads to a deceleration of the flow in the lower gap region and the flow becomes more uniform in the top region.

Tardy and Bittleston (2015) present a mathematical and numerical model to solve the flow and displacement of completion fluids in the annular space. They showed that as the absolute eccentricity increases, the fraction of the flow through the wider part of the annulus increases too, and suggest that an optimum eccentricity may exist with value next to the maximum eccentricity value.

Vieira Neto *et al.* (2012) in an experimental and numerical study analyzed the eccentricity effects of non-Newtonian fluids flowing through annuli with the variable eccentricity motion of the inner tube. They conclude that the eccentricity adversely affects the pressure drop, since the most eccentric section presented the lowest pressure drop.

It is fact that the cuttings removal has a great importance on drilling process. An inefficient cuttings transport interferes in the drilling velocity, rising the time and the cost of the operation. Under the circumstances, studies are carried in order to understand the influence of each parameter of the cuttings removal process aiming to optimize and improve the wellbore cleaning efficiency. This study uses computational fluid dynamics (CFD) in order to evaluate the eccentricity effects on the performance of the cleaning process. Axial and tangential velocity, pressure drop and effective viscosity will be analysed.

2. BASIC EQUATIONS

The equations governing the flow for the cases analyzed in this paper are:

Continuity equation:

$$\nabla.\vec{V} = 0 \tag{1}$$

Navier-Stokes equation:

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

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.

The Cross viscosity equation represents the rheological model used. It is a four parameters model used to represent shear-thinning fluids. This model is represented, according Chhabra and Richardson (2008), by Eq. (3).

$$\frac{\mu - \mu_0}{\mu_0 - \mu_\infty} = \frac{1}{1 + k(\dot{\gamma}_{xy})^n} \tag{3}$$

In the above equation, the power index (n) is smaller than one and together with the consistency index (k) are two fitting parameters, while μ_0 and μ_∞ are the limiting values of effective viscosity at low and high shear stress, respectively, and $\dot{\gamma}_{xy}$ is the shear strain (s^{-1}).

3. METHODOLOGY

This study uses Computational Fluid Dynamics (CFD), *software* Ansys® CFX 16.0 *preview* 4, in order to evaluate the eccentricity effects on fully developed laminar fluid flow of non-Newtonian fluid through an annuli. The geometry was based on the study of Escudier *et al.* (2002b) and consists of two cylinders. The outer cylinder, with 0.0502 m radius (r_o), is static and the inner cylinder, with 0.0254 m radius (r_i), rotates with a constant speed. Both cylinders were 5.775 m long.

Eccentricity (ε) is a dimensionless parameter, which is equal to zero for a concentric annulus and one for a fully eccentric case, it is defined by Eq. (4), where "e" is the distance between the centers of the inner and outer cylinders and δ is the difference of the outer radius and the inner radius. The dimensionless distance from inner cylinder (σ), in the region between the inner cylinder and the outer wall, is defined by Eq. (5), where "y" is the radial distance measured from inner cylinder and "s" is the gap width. Fig. 1 shows the schematic representation of the geometry studied.

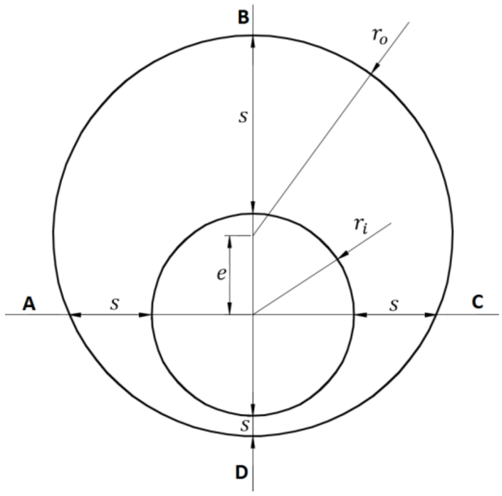
$$\varepsilon = \frac{e}{\delta} \tag{4}$$

$$\sigma = \frac{y}{s} \tag{5}$$

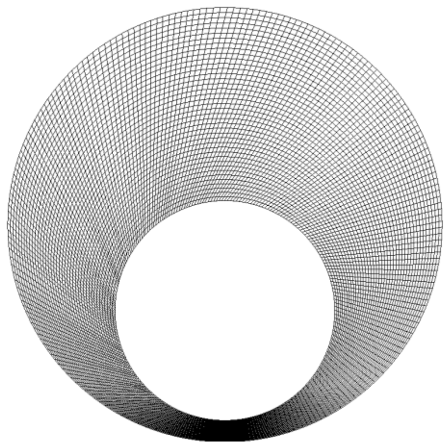
The drilling fluid used, based on Escudier *et al.* (2002b) study, is an aqueous solution of 0.1% xanthan-gum and 0.1% carboxymethylcellulose (CMC) and the non-Newtonian characteristics of the fluid is represented by the rheological Cross model. Tab.1 shows the drilling fluid parameters. Five eccentricity values were evaluated, varying from $\varepsilon = 0$ (concentric case) to $\varepsilon = 0.8$.

A structured mesh was used for the simulations, the mesh independent condition was verified for the critical case ($\varepsilon = 0.8$). To control the number of elements on the azimuthal direction, the minimum and maximum face sizes were set to 0.001 m, the number of divisions was 40 in the radial direction and 256 in the axial direction.

The simulations were carried out in the steady state regime and the convergence criteria used was $1\text{x}10^{-4}$. The boundary conditions adopted were: axial velocity U = 0.268 m/s at the entrance, inner rotation speed of 5.24 s^{-1}, and outlet opening condition with relative pressure set to 0 Pa.



a) Geometric parameters



b) Computational mesh – 40x256 divisions

Figure 1. Schematic representation of the geometric parameters and mesh for the eccentric annulus.

Table 1. Rheological fluid parameters.

Cross parameters	
μ_0 (Pa.s)	0.262
μ_∞ (Pa.s)	0.00144
K (s^n)	2.414
n	0.504

4. RESULTS

In this section we present the results of the simulations. The obtained results will be presented in two parts. At first, the numerical model validation is shown. The experimental data of Escudier *et al.* (2002b) were used to validate the model. In the second part, the effects of eccentricity on the dimensionless axial velocity are shown, followed by the effects on the dimensionless tangential velocity profiles, pressure drop and effective viscosity.

4.1 Validation of CFD computational model

In this section, the CFD model is validated using the experimental data of Escudier *et al.* (2002b). The boundary conditions to validate were: axial velocity U = 0.268 m/s at the entrance, inner rotation speed of 5.24 s^{-1} and eccentricity ε = 0.8.

According to Fig. 2 the dimensionless axial velocity simulated in this work showed a good agreement with the work of Escudier *et al.* (2002b). The axial velocity distortion due to eccentricity observed by Escudier *et al.* (2002b) was also observed by the numerical approach, a flat profile at the wider gap due to the shear-thinning characteristics of the fluid was observed too. The relative error for the maximum velocity at the top gap was 3% and at the bottom gap 17%. A good agreement was also observed for the dimensionless tangential velocity, with the recirculation zone reported by Escudier *et al.* (2002b) in almost whole top gap (Sector B) also been observed in the present study. The relative error in this Sector (top gap) was 3%. Therefore, the numerical model is validated in order to carry the study in the eccentric annulus evaluated in this work.

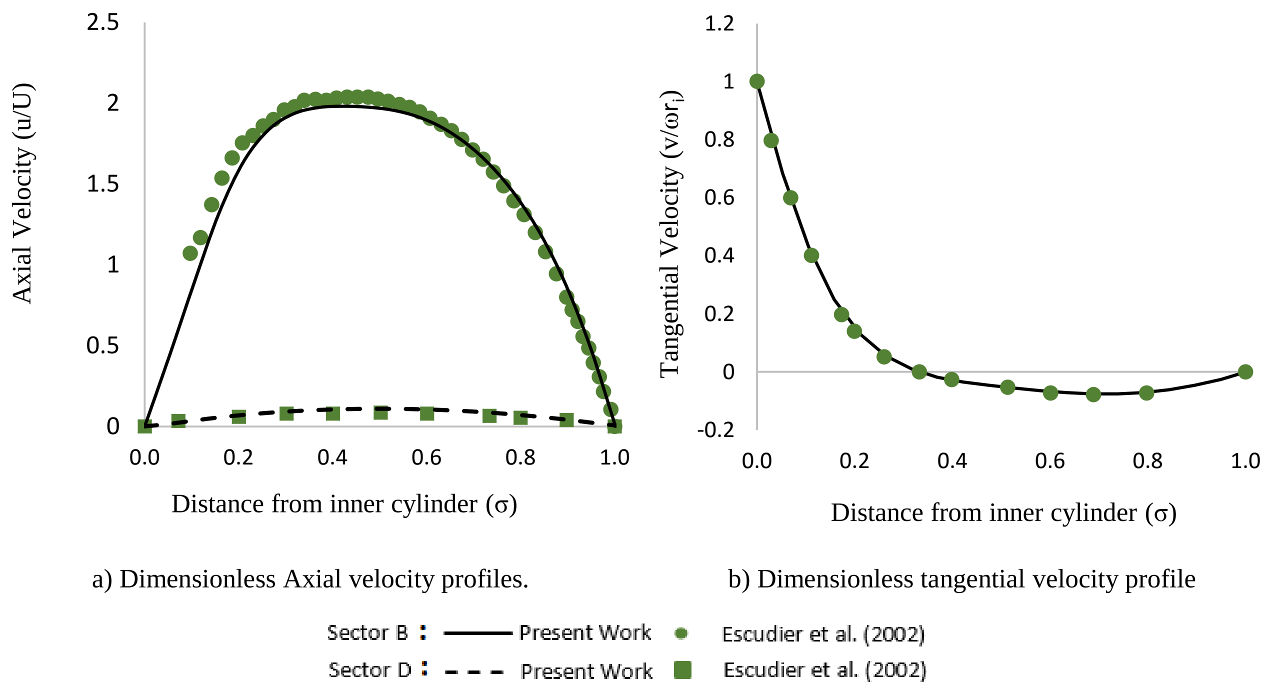


Figure 2. Comparison between the present numerical study and the experimental data of Escudier *et al.* (2002b).

4.2 Eccentricity effects

Figure 3 presents the dimensionless axial velocity profile in the annulus. According the figure, as eccentricity increases, the magnitude of the axial velocity on the top gap (Sector B) increases too. The opposite effect occurs on the lower gap (Sector D), where the axial velocity reduces as the eccentricity increase. Similar effects were reported by Fang *et al.* (1999), Pereira *et al.* (2006), Pereira *et al.* (2007) and Siqueira *et al.* (2014). This effect can be negative to the wellbore cleaning process, considering that with a low velocity, the cuttings transport will be difficult and the cuttings would be accumulated at the bottom of the annular, forming a bed.

Figure 4 shows the dimensionless velocity contours for each studied eccentricity and the effects described above are more evident. According to this figure, the maximum velocity core is displaced to the top of the gap as the eccentricity increases. The reason for this behavior is the top gap is a zone with lower resistance to the flow and, therefore, the flow at the bottom becomes almost stagnant, what can be prejudicial to the wellbore cleaning process. Similar results were observed by Fang *et al.* (1999), Li *et al.* (2012), Ogugbue and Shash (2012), Pereira *et al.* (2006) and Vieira Neto *et al.* (2014).

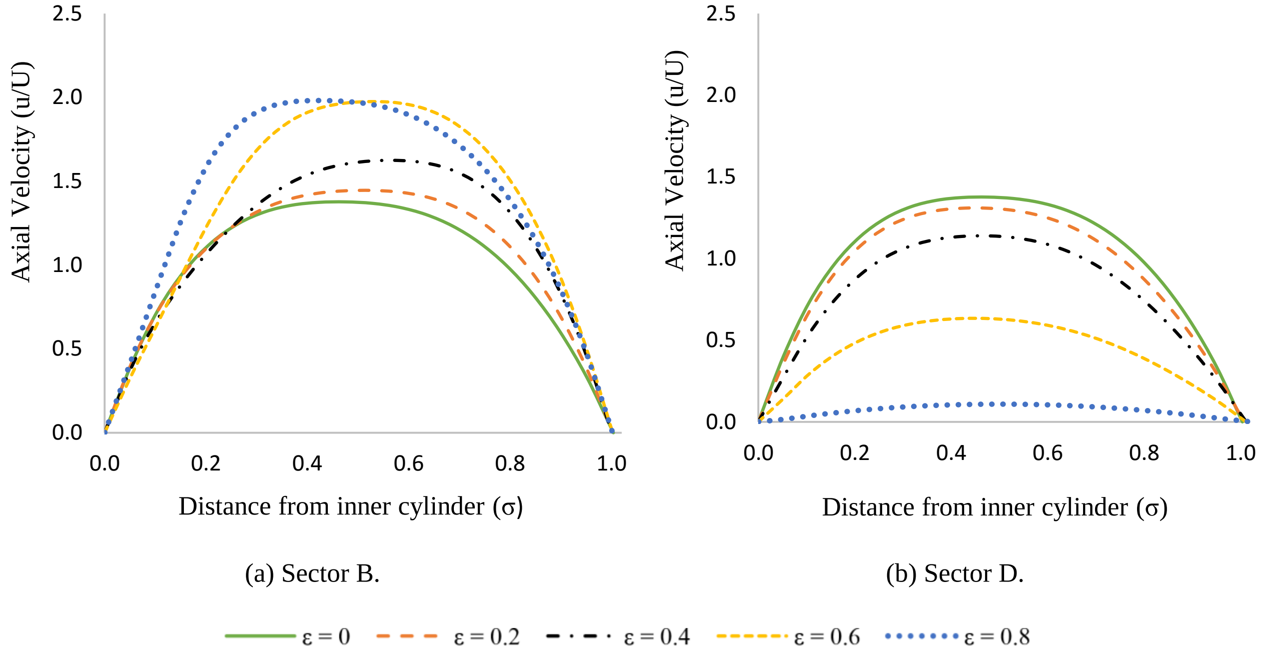


Figure 3. Eccentricity effects on dimensionless axial velocity profiles.

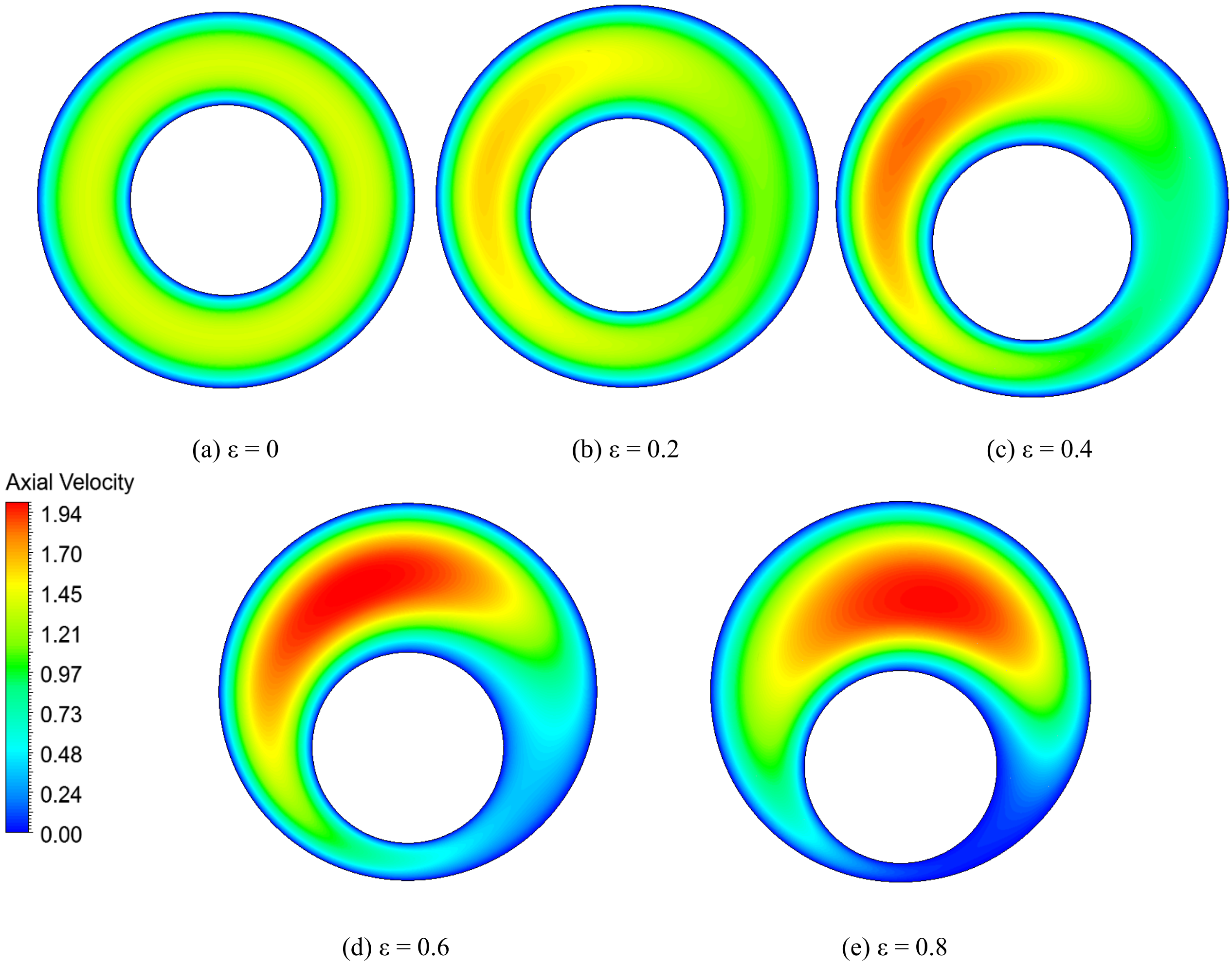


Figure 4. Eccentricity effects on dimensionless axial velocity contours.

The tangential velocity is an important parameter to be observed and Fig. 5 shows the effect of eccentricity on this parameter. According to this figure, the rise on the eccentricity increases the tangential velocity at the narrowest gap (Superior lines), what could be good to the cleaning process. According to Sun *et al.* (2014), high tangential velocities are good to suspend and drag the cuttings, because the cuttings are tangentially dragged by the drilling fluid viscous forces. The opposite effect is observed at the wider gap (Inferior lines) and a negative velocity is observed for high eccentricity values, which may indicates the presence of counter-rotating eddies in this sector. The similar results were reported by Vieira Neto *et al.* (2014) and Siginer and Bakhtiyarov (1998)

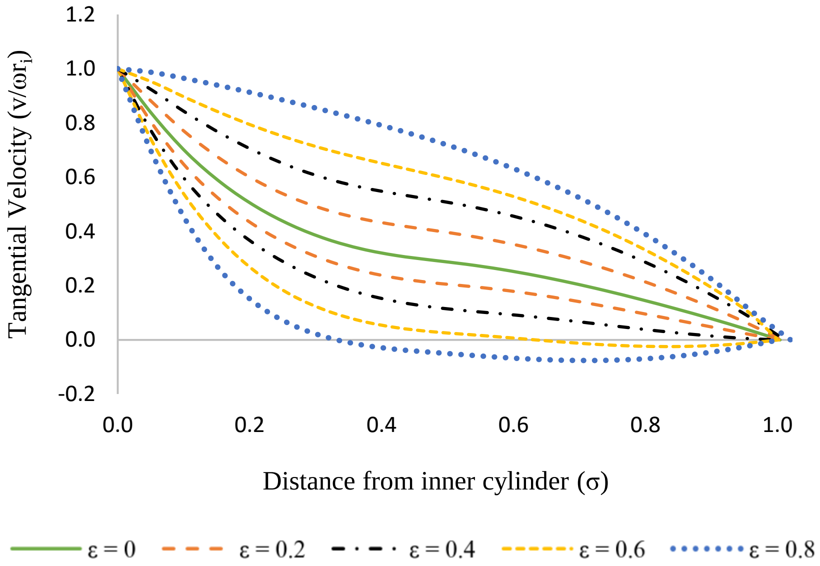


Figure 5. Eccentricity effects on dimensionless tangential velocity profiles.

Figure. 6 shows the eccentricity effects on pressure profile along the axial direction. According these results, the increase of eccentricity causes a reduction on the pressure drop. We observe that for small eccentricities ($\varepsilon \leq 0.4$) the pressure drop reduction was small compared to the concentric case, however, to high eccentricities values ($\varepsilon > 0.5$), the pressure drop reduction was significant and reach as much as 32% for the $\varepsilon = 0.8$ case. Pereira *et al.* (2007) and Vieira Neto *et al.* (2012) reported similar results, showing that the most eccentric case had the lowest pressure drop, comparing to concentric case.

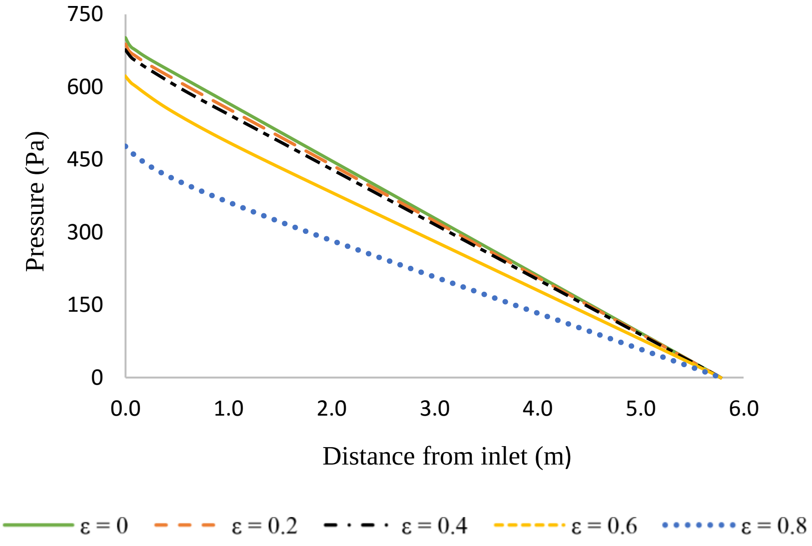


Figure 6. Eccentricity effects on pressure profile along axial direction.

Figure 7 shows the eccentricity effects on viscosity profiles at the narrowest gap. According to the figure, an increase of eccentricity reduces the viscosity in this section of the annular (Approximately 57% for the $\varepsilon = 0.8$ case), what could be prejudicial to the cleaning process, because a low viscosities reduce the ability of the fluid to carry the particles away, forming a cutting bed. Ogugbue and Shash (2012) reported similar results for a shear-thinning fluid.

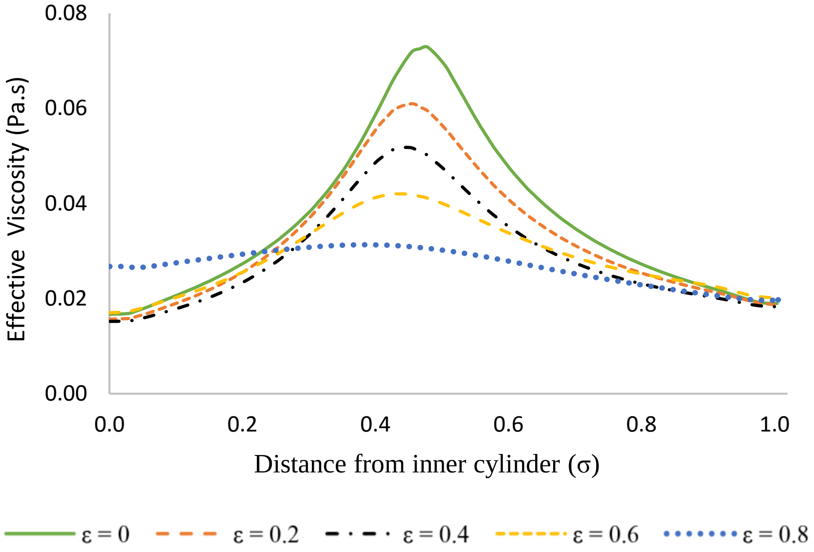


Figure 7. Eccentricity effects on effective viscosity profiles at the sector D.

5. CONCLUSION

The numerical simulations of non-Newtonian fluid flow through an annulus presents a contribution to understand the effects of eccentricity on the flow pattern and the consequences on the horizontal wellbore cleaning process. The CFD code proved to be an efficient tool to approach non-Newtonian fluid flow in eccentric annular geometries, showing a good agreement between the computational results and the experimental data available in the literature.

The increase of eccentricity causes a considerable reduction of axial velocity at the narrowest gap, what is prejudicial to the cutting removal and, consequently, to the cleaning process, because the low axial velocity difficult the maintenance of the suspended cuttings, tending the cuttings to sediment at the bottom of the annular. At the widest gap the opposite effect was observed. The tangential velocity is affected by the increase of eccentricity, once that, as the eccentricity increases, the tangential velocity at bottom gap also increases. This behavior could be benign to suspend the cuttings, providing their transport by the axial flow. In the top gap, the eccentricity increase reduces the tangential velocity and the presence of counter-rotating eddies was noted to high eccentricity values. Concerning the pressure drop, it was observed that the lowest pressure drop occurs in the most eccentric case. At last, it is possible to conclude that the eccentricity affects the viscosity, reducing the effective viscosity as the eccentricity increases, what would be prejudicial to cutting transport, since a low viscosity value reduces the fluid ability to alter the drag velocity of particles.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Caenn, R. and Chillingar, G.V., 1996. "Drilling fluids: state of the art". *Journal of Petroleum Science and Engineering.* Vol. 14, pp. 221-230.

Chhabra, R.P. and Richardson, J.F., 2008. *Non-Newtonian Flow and Applied Rheology*, Butterworth-Heinemann, Oxford, 2nd edition.

Escudier, M. P., Oliveira, P. J., and Pinho, F. T., 2002a. "Fully developed laminar flow of purely viscous non-Newtonian liquids through annuli, including the effects of eccentricity and inner-cylinder rotation". *International Journal of Heat and Fluid Flow*, Vol. 23, pp. 52-73.

Escudier, M.P., Gouldson, I., Oliveira, P.J., and Pinho, F.T., 2002b. "Fully developed laminar flow of non-newtonian liquids through annuli: comparison of numerical calculations with experiments". *Experiments in Fluids*, Vol. 33, pp. 101-111.

Fang, P., Manglik, R. M., and Jog, M. A., 1999. "Characteristics of laminar viscous shear-thinning fluid flows in eccentric annular channels". *Journal of non-Newtonian fluid mechanics*, Vol. 84, pp. 1-17.

Li, M., Wang, R., Wang, C., Fang, Q. and Xue, Y., 2013. "Study on flow characteristic of non-Newtonian fluid in eccentric annulus". *Research Journal of Applied Sciences, Engineering and Technology*, Vol. 6, pp. 2451-2458.

Loureiro, B.V., Siqueira, R.N., 2006. "Determinação da tensão de cisalhamento mínima para arraste de partículas de um leito sedimentado". *Proceedings of the Encontro Nacional de Hidráulica de Perfuração e Completação de Poços de Petróleo e Gás – ENAHPE2006.* Domingos Martins, Brazil.

Ogugbue, C.C.E. and Shash, S.N., 2012. "CFD modeling of non-Newtonian flow in eccentric annular geometries". *International Journal of Petroleum Science and Technology*, Vol. 6, n. 1, pp. 9-34.

Pereira, F.A.R, Ataíde, C.H. and Barrozo, M.A.S., 2006. "Abordagem de CFD com modelo de fase discreta para análise do escoamento anular". In *Proceedings of the Encontro Nacional de Hidráulica de Perfuração e Completação de Poços de Petróleo e Gás – ENAHPE2006.* Domingos Martins, Brazil.

Pereira, F.A.R, Ataíde, C.H. and Barrozo, M.A.S., 2007. "CFD predictions of drilling fluid velocity and pressure profiles in laminar helical flow". *Brazilian Journal of Chemical Engineering*, Vol. 24, n. 4, pp. 587-595.

Siginer, D. A., Bakhtiyarov, S. I., 1998. "Flow of drilling fluids in eccentric annuli". *Journal of Non-Newtonian Fluid Mechanics,* Vol. 78, pp. 119-132.

Siqueira, R.N., Rigatto, S.F., and Furini, T.M.G., 2014. "Effects of drill pipe eccentricity on horizontal wells drilling". In *Proceedings of the Rio Oil & Gas Expo and Conference 2014.* Rio de Janeiro, Brazil.

Sun, X., Wang, K., Yan, T., Shao, S., Jiao, J., 2014. "Effect of drillpipe rotation on cuttings transport using computational fluid dynamics (CFD) in complex structure wells". *Journal of Petroleum Exploration and Production Technology*, Vol. 4, pp. 255-261.

Tardy, P. and Bittleston, S., 2015. "A model for annular displacements of wellbore completion fluids involving casing movement". *Journal of Petroleum Science and Engineering*, Vol. 126, pp. 105-123.

Vieira Neto, J. L., Martins, A. L., Ataíde, C. H. and Barrozo, M. A. S., 2012. "Non-Newtonian Flows in Annuli with Variable Eccentric Motion of the Inner Tube". *Chemical Engineering Technology*, Vol. 35, pp. 1981-1988.

Viera Neto, J. L., Martins, A. L., Ataíde, C.H., Barrozo, M. A. S., 2014. "The effect of the inner cylinder rotation on the fluid dynamics of non-Newtonian fluids in concentric and eccentric annuli". *Brazilian Journal of Chemical Engineering*, Vol. 31, n. 4, pp. 829-838.

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