CFD ANALYSIS OF ECCENTRICITY EFFECTS ON HORIZONTAL WELLS CLEANING PROCESS

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Abstract: *On the drilling process, drill pipe rotation and the weight applied to the bit is what promotes the rock fragmentation. The drilling fluid injected into the column removes these cuttings and return to the surface through the annular space. For horizontal wells, the drill string is usually displaced, due to gravitational effects, generating an eccentric configuration that changes the flow pattern and creates a sedimentation bed, which affects the wellbore cleaning process. This study uses computational fluid dynamics (CFD) in order to evaluate the eccentricity effects on the cleaning process performance. The drilling fluid is a standard fluid, used by a big petroleum company, with non-Newtonian characteristics represented by the Herschel-Bulkley rheological model. The geometry consists of two cylinders. The outer cylinder is static and the inner cylinder rotates, with rotational speed varying from* $\omega = 0$ *to* $\omega = 400$ *rpm. The axial flow is characterized by the Reynolds number, which varies from 200 to 1000. Two diameters ratio were evaluated (*$k = 0.5$ *and* $k = 0.9$*). For all the configurations specified above, five eccentricity values were analysed, varying from* $\varepsilon = 0$ *(concentric case) to* $\varepsilon = 0.8$*. The study shows a reduction of the axial velocity in the narrow gap with an increase of eccentricity, which would difficult the cuttings transport and form a cuttings bed at the bottom of the annular. This negative effect is compensated by an increase of the tangential velocity in this sector, which improves the cleaning process efficiency. The study also shows that the increase in eccentricity cause a reduction of pressure drop, demanding less energy to remove the cuttings.*

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

1. INTRODUCTION

The non-Newtonian fluid flow in annular spaces has great relevance in various industry sectors such as chemical, food and oil. One of the most important application in the oil industry is the drilling operation. On the drilling process, drill pipe rotation and the weight applied to the bit is what promotes the rock fragmentation. The drilling fluid injected into the column removes these cuttings and returns to the surface through the annular space carrying the cuttings. For horizontal wells, the drill string is usually displaced, due to gravitational effects, generating an eccentric configuration that changes the flow pattern and creates a sedimentation bed, which affects the wellbore cleaning process. According to Caenn and Chillingar (1996), drilling fluids are a complex mixtures of liquids, chemical products and solids and its main function is the cuttings removal.

The cuttings transport is affected by many parameters such as particle size, wellbore geometry, drill pipe rotation, fluid rheology, axial flow rate and drill pipe eccentricity, which has a great importance in the process. (Ooms and Burgercentrum, 1999; Fang *et al.*, 1999; Sorgun *et al.*, 2011; Ofei *et al.*, 2015).

The cuttings transport problem have been investigated by many authors in literature. Ooms and Burgercentrum (1999), in a analytic, numerical and experimental study, analyses the effects of drill pipe rotation and eccentricity in the pressure drop over a borehole during drilling. The authors showed that the eccentricity and rotation increases the pressure drop.

Fang *et al.* (1999) shows, due to the geometry and fluid rheology effects, a bad distribution of flow pattern in the annulus, leading to a stagnant flow at the narrowest section and a non uniform shear stress over the wellbore wall.

Ogugbue and Shah (2012), investigated the effect of eccentricity and diameter ratios on axial velocity and viscosity profiles. They concluded that the narrowest region of the annular presents a high shear zone, causing a considerable viscosity reduction in this region.

Mingzhong *et al.* (2013) and Tardy and Bittleston (2015), shows that as the eccentricity increases, the flow fraction through the wider gap also increases and the flow at the narrowest gap became almost stagnant.

Erge *et al.* (2014; 2015), experimentally, analysed the eccentricity effects in the pressure drop over the annular. The authors showed that the eccentricity can cause a reduction of the pressure drop in the annular (more than 50% in some cases). The authors emphasize that eccentricity must be taken into account during hydraulic planning for horizontal and extended reach wells.

GhasemiKafrudi and Hashemabadi (2016), numerically, investigated the fluid flow of drilling fluid and cuttings in vertical wells. The authors observed that eccentric cases showed lower pressure drop compared with the concentric case; and they concluded that the eccentricity is detrimental to the wellbore cleaning process.

The annular fluid flow pattern must be studied because a inefficient cuttings removal affects the drilling operation, causing a decrease of the rate of penetration, loss of circulation and obstruction of annular space. It may also compromise the wellbore integrity and stuck the column, stopping the operation and rising the time and operational costs.

Analysing the complete drilling process problem is complicated since some field parameters, such as drilling fluid rheology, formation characteristics and eccentricity, are specific and changes in each situation. Considering it, the idealized analysis are suitable to provide more information to understand the process and try to solve the real problems.

Under the above circumstances, studies are carried out 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 velocities and also pressure drop along the annular were analysed.

2. BASIC EQUATIONS

2.1 Motion equations

The equations governing the flow for the cases analysed 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.

2.2 Herschel-Bulkley rheological model

The Herschel-Bulkley fluid model is used to represent the behaviour of non-Newtonian viscoplastic fluids. The equation that represents the model is described, according to Chhabra and Richardson (2008), by the Eq. (3).

$$\tau = \tau_0 + K\dot{\gamma}^n \tag{3}$$

In the above equations, τ is the shear stress, τ_0 is yield stress, K is the consistency index, n is the behaviour index, $\dot{\gamma}$ is the shear strain.

2.3 Generalized Reynolds number

The generalized Reynolds number was calculated using the relation of Madlener *et al.* (2009), defined by the Eq. (4)

$$Re = \frac{\rho\bar{u}^{2-n}{D_h}^n}{(\tau_0/8)(D_h/\bar{u})^n + K[(3m+1)/(4m)]^n 8^{n-1}} \tag{4}$$

Where m is the local shear stress gradient, defined by Eq. (5) and D_h is the hydraulic diameter, defined by Eq.(6).

$$m = \frac{nK(8\bar{u}/D_h)^n}{\tau_0 + K(8\bar{u}/D_h)^n} \tag{5}$$

$$D_h = D_o - D_i \tag{6}$$

The critical Reynolds number was calculated following the expression of Khataniar *et al.* (1994), defined by Eq. (7).

$$Re_c = 3470 - 1370n \tag{7}$$

3. METHODOLOGY

This study uses computational fluid dynamics (CFD), software Ansys CFX 16.0, in order to evaluate the eccentricity effects on fully developed laminar flow of non-Newtonian fluid through an annuli. The drilling fluid is a standard fluid, used by a big petroleum company, with non-Newtonian characteristics represented by the Herschel-Bulkley rheological model, Tab. 1 shows the drilling fluid parameters.

Table 1: **Rheological fluid parameters**

τ_0 (Pa)	17.81
K (Pa.s)	0.26
n	0.74

The geometry consists of two cylinders; The outer cylinder is static, with diameter determined by the diameters ratio and the inner cylinder, with 0.0508 m diameter, rotates, with rotational speed varying from ω = 0 to ω = 400 rpm. Both cylinders were 2.5 m long. The geometry is represented by Fig. 1, where the sectors are identified by the letters: A, representing the superior gap, B and D the lateral gaps and C the bottom gap.

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 as ($\varepsilon = e/r_o - r_i$), where "e" is the distance between the centers of the inner and outer cylinders. The dimensionless distance from inner cylinder (σ), in the region between the inner cylinder and the outer wall, is defined as (y/s), where "y" is the radial distance measured from inner cylinder and "s" is the gap width.

The axial flow is characterized by the Reynolds number, which varies from 200 to 1000. Two diameters ratio were evaluated (k = 0.5 and k = 0.9). For all the configurations specified above, five eccentricity values were analysed, varying from ε = 0 (concentric case) to ε = 0.8.

A structured mesh was used for the simulations, the independent condition was verified for the critical case (ε = 0.8) and the mesh had: 90 divisions in the radial direction, 108 in the axial direction and 220 in the azimuthal direction.

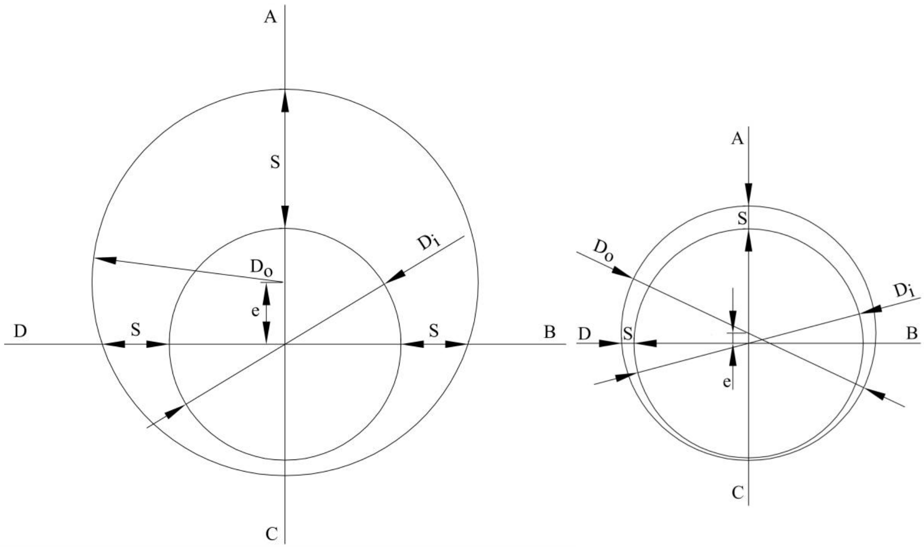


Figure 1: **Schematic representation of the geometric parameters.**

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 Nouar *et al.* (1998) were used to validate the model. In the second part, the effects of eccentricity are shown.

4.1 CFD model validation

In this section the CFD model is validated with the experimental data of Nouar *et al.* (1998). Fig. 2 presents the axial velocity simulated in this work. The simulated profile showed a good agreement with the work of Nouar *et al.* (1998). The relative error for the maximum velocity was 1% and the error for the average velocity was 0.61%. The simulation conditions were axial velocity at the entrance (U = 0.0728 m/s) and constant inner cylinder rotation speed (ω = 268.2 rpm).

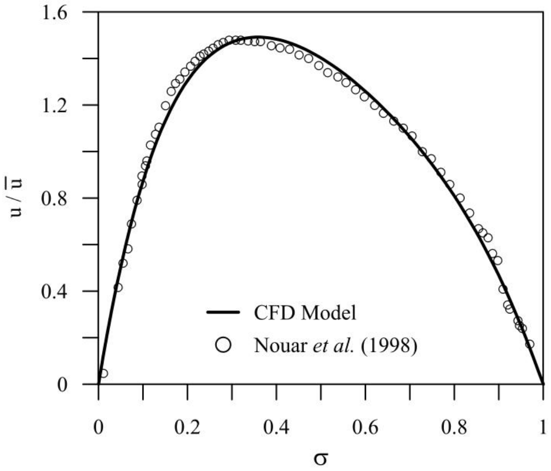


Figure 2: **Comparison between the present numerical study and the experimental data of Nouar *et al.* (1998).**

4.2 Eccentricity effects

In this section the eccentricity effects are presented for both cases investigated: without inner cylinder rotation (ω = 0 rpm) and with inner cylinder rotation (ω = 400 rpm).

4.2.1 Non-rotational cases (ω = 0 rpm)

Figure 3 presents the dimensionless axial velocity profile at the bottom gap (Sector C). According to the figure, the axial velocity in this region reduces as the eccentricity increases. For the most eccentric case, it's possible to notice a stagnant flow for all Reynolds numbers analysed and for low diameter ratio, which is prejudicial to the wellbore cleaning process, once the low fluid velocity will not carry the cuttings efficiently and the cuttings would settled down, forming a bed.

For low diameter ratio, the velocity profile have a flat shape, except for the most eccentric case (ε = 0.8), which indicates a high viscosity in this region. This behaviour is good for the cleaning process once high viscosity helps to keep the cuttings suspended, preventing the cuttings bed formation and their removal from the wellbore. For high diameter ratio (k = 0.9) and high Reynolds number (Re = 1000), the flat shape was observed just for the concentric case (Fig. 3d).

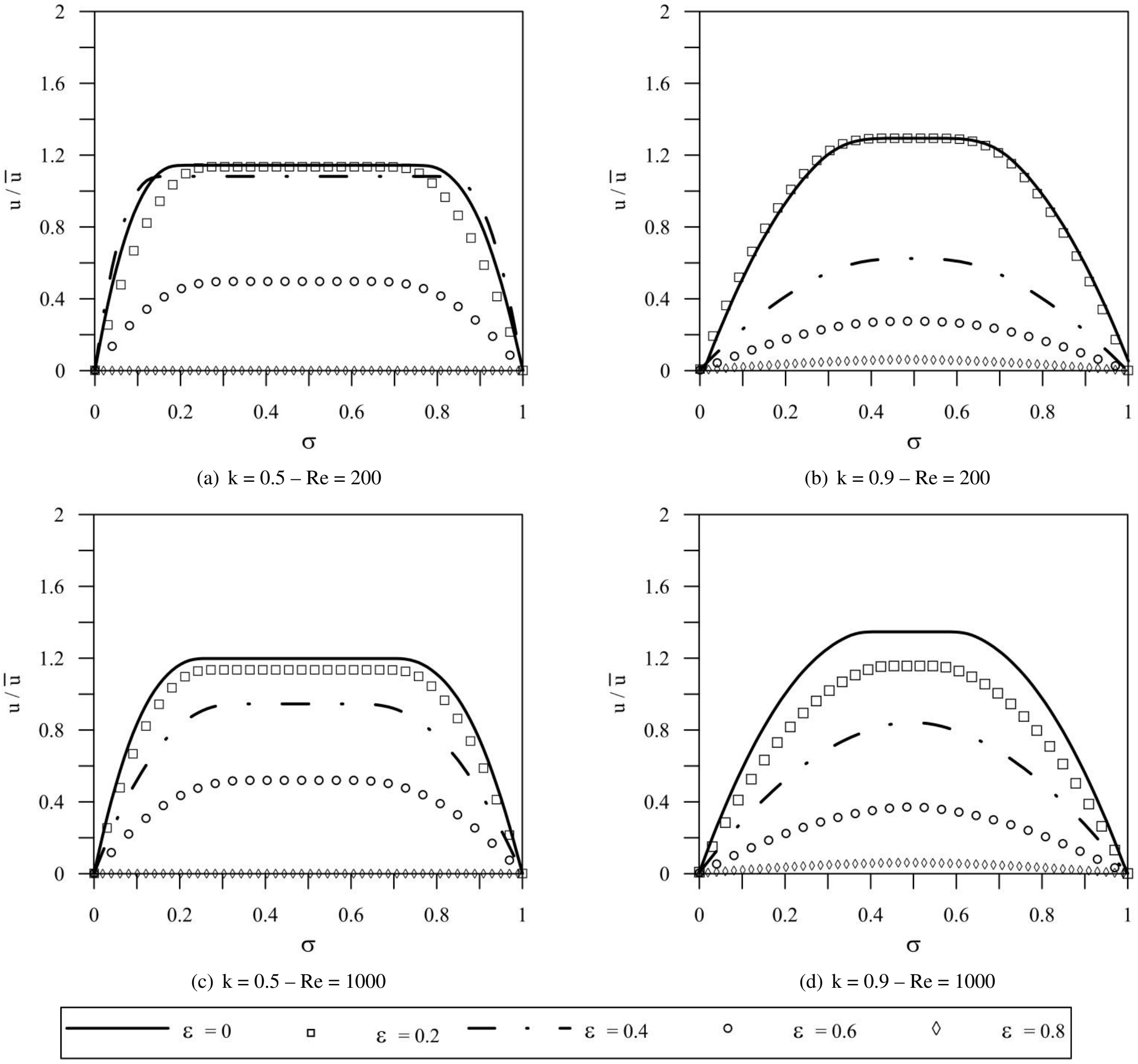
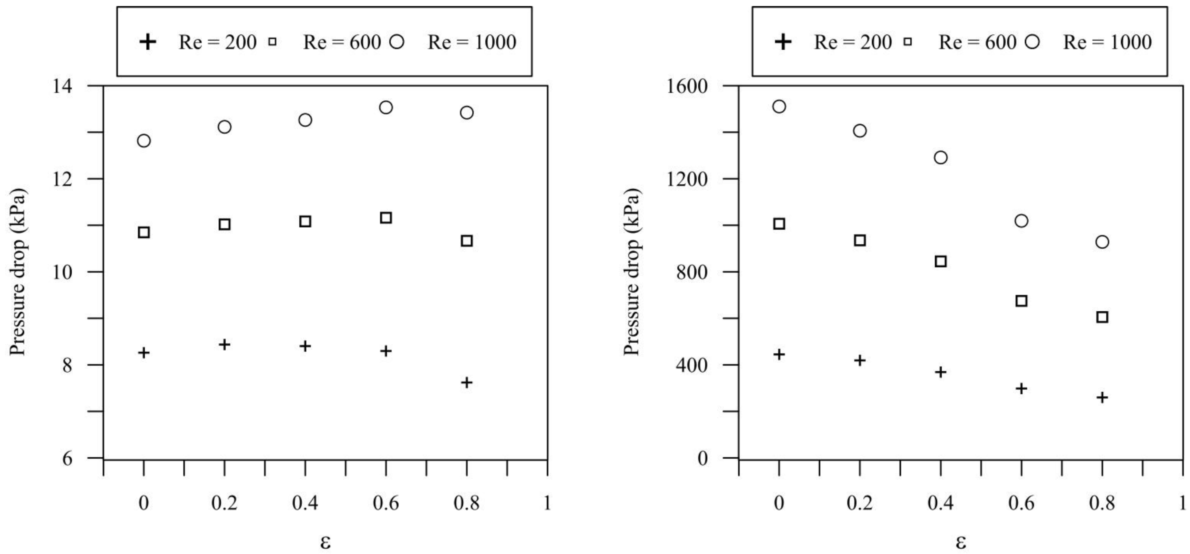


Figure 3: **Eccentricity effects on dimensionless axial velocity profiles.**

Figure 4 presents the eccentricity effects on pressure drop in the annular. According to the figure, the increase of eccentricity cause a reduction of pressure drop, except for high Reynolds number and low diameter ratio case. The most eccentric case of the high diameter ratio case shows a reduction of 63%, compared to concentric case. Erge *et al.* (2014, 2015), Lídio and Siqueira (2015) reported similar results. Ooms and Burgercentrum (1999) reported that for low eccentricity values (ε < 0.4) the pressure drop increases as the eccentricity increases too. The same behaviour was noticed for the low diameter ratio case.

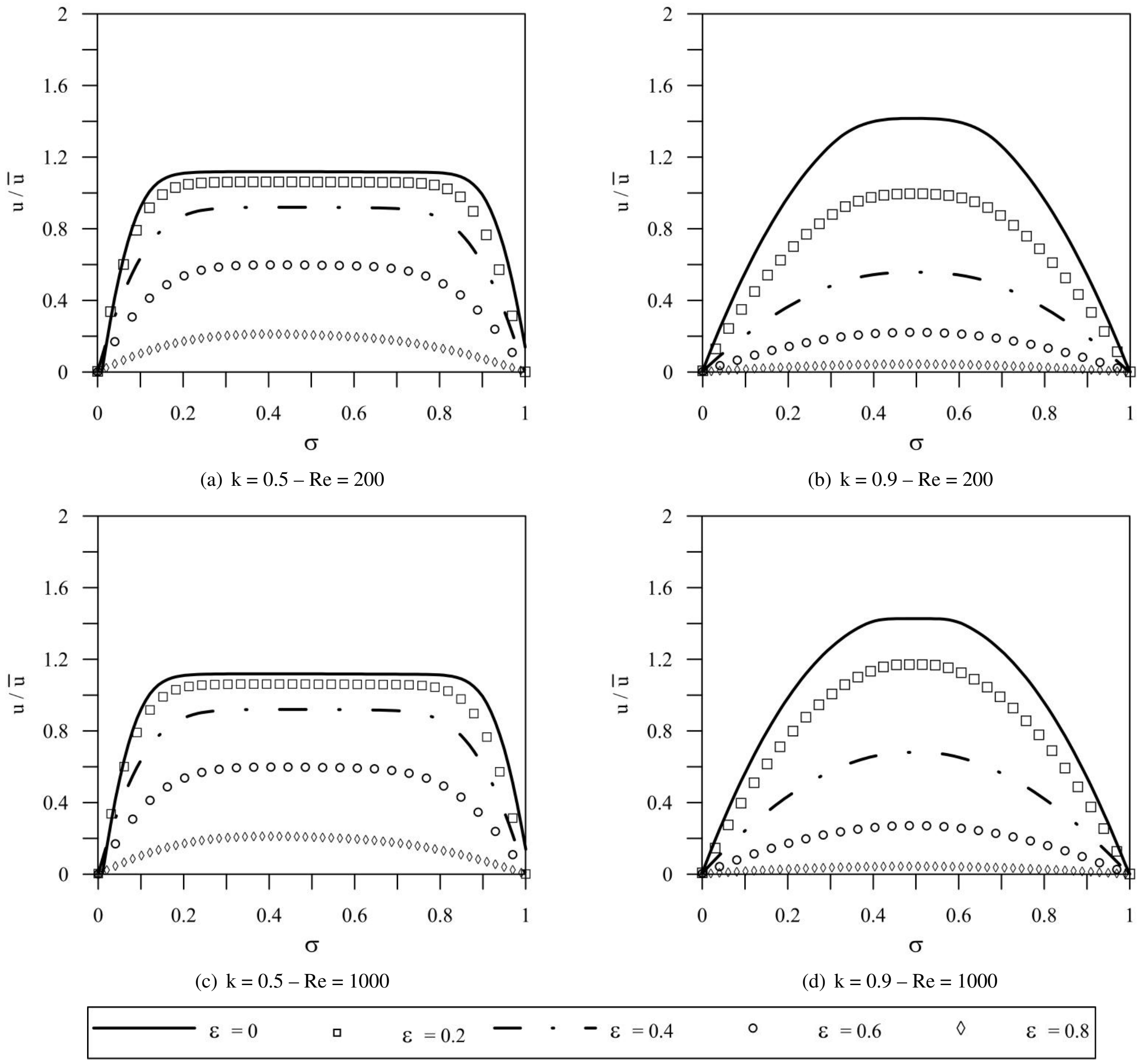


(a) k = 0.5
(b) k = 0.9

Figure 4: **Eccentricity effects on pressure drop.**

4.2.2 Rotational cases (ω = 400 rpm)

Figure 5 shows the eccentricity effects on axial velocity profiles for high rotational speeds at the bottom gap (Sector C).



(a) k = 0.5 – Re = 200
(b) k = 0.9 – Re = 200
(c) k = 0.5 – Re = 1000
(d) k = 0.9 – Re = 1000

Figure 5: **Eccentricity effects on dimensionless axial velocity profiles for high rotational speeds**

The axial velocity profile have the same reduction tendency of the case without rotation. For the most eccentric case, the velocity increased, compared to the cases without rotation. The effects of drill pipe rotation are present for low Reynolds number, where we can observe a distortion of velocity profile for high eccentricities. This axial velocity increase for the most eccentric case is good for the cleaning process.

Figure 6 presents the eccentricity effects on tangential velocity profiles.

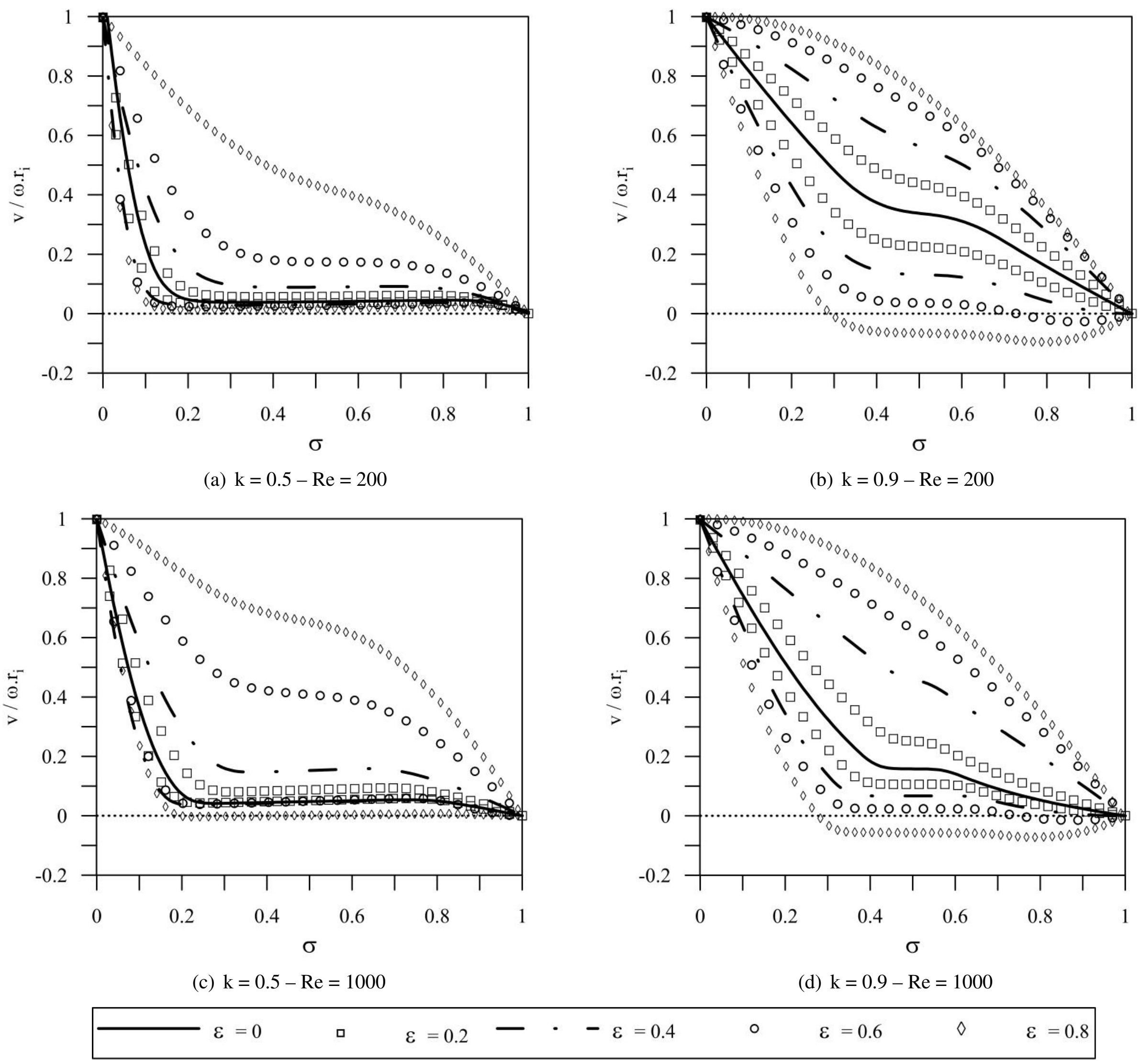


Figure 6: **Eccentricity effects on dimensionless tangential velocity profiles.**

According to the figure, the tangential velocity tends to reduce with a increase of eccentricity for the wider gap (inferior lines) for all studied cases, with almost zero velocity at the major portion of the gap for low eccentricities values.

For the case with high diameter ratio, the most eccentric case presents negative tangential velocities in a major portion of the gap, indicating a recirculation zone with a presence of counter-rotating eddies in this sector. The recirculation zone helps to keep the cuttings in suspension, preventing its sedimentation.

At the narrow gap (superior lines), an increase of tangential velocity was observed as the eccentricity increases, with the presence of high velocity gradients near the wellbore wall for high eccentricities case and this gradients are greater for high diameter ratio cases. This behaviour could help the cuttings suspension once that the cuttings are tangentially dragged by the viscous fluid forces. Same results were reported by Vieira Neto *et al.* (2014).

Figure 7 presents the eccentricity effects on pressure drop along the wellbore. The figure shows a reduction of pressure drop with the increase of eccentricity. This effect is more evident for high Reynolds values.

This reduction is beneficial to the process because it will demand less energy to pump the drilling fluid and prevent some drilling problems related to the reservoir pore pressure, where drilling fluid loss that may cause a blow-out.

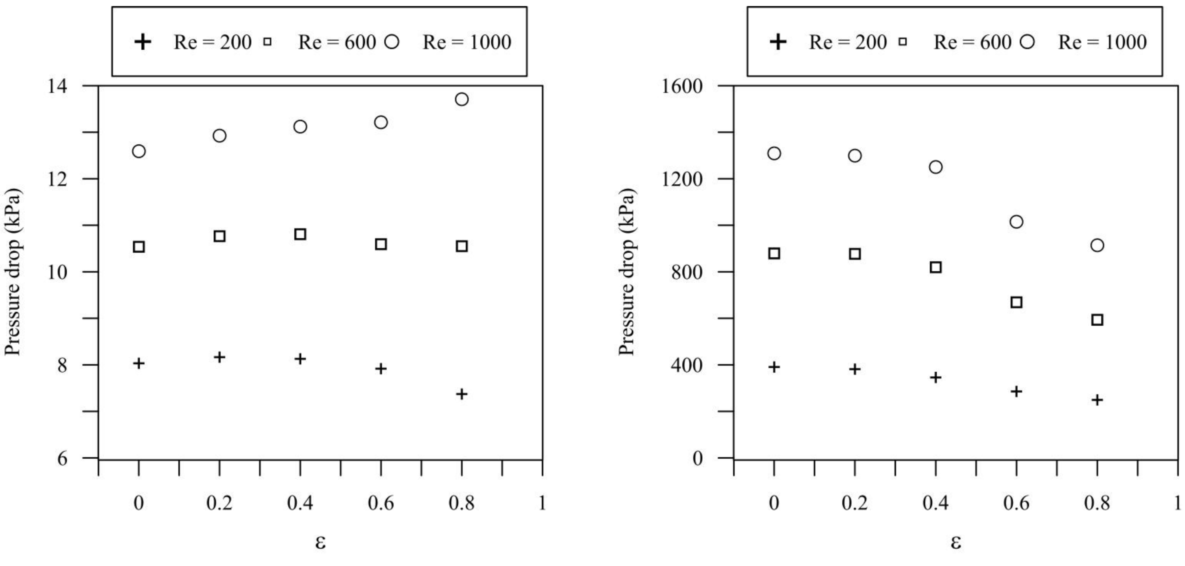


Figure 7: **Eccentricity effects on pressure drop.**

5. CONCLUSIONS

The CFD model proved to be an efficient tool to approach non-Newtonian fluid flow in eccentric annular geometries with inner cylinder rotation, 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, causing a stagnant flow for low diameter ratio and non-rotational cases, which is prejudicial to the cuttings 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. For high diameter ratio the velocity increase for the most eccentric case ($\varepsilon = 0.8$).

For the rotational cases the axial velocity profile have the same reduction tendency of the case without rotation. For the most eccentric case, the velocity increased, compared to the cases without rotation, mainly for the low diameter ratio cases. The effects of drill pipe rotation are present for low Reynolds number, where we can observe a distortion of velocity profile for high eccentricities.

The tangential velocity is affected by the increase of eccentricity, once as the eccentricity increases, the tangential velocity at bottom gap also increases. This behaviour 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.

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. and Richardson, J., 2008. *Non-Newtonian flow and applied rheology*. Butterworth-Heinemann, Oxford, 2nd edition. ISBN 9780750685320.

Erge, O., Karimi Vajargah, A., Ozbayoglu, M.E. and van Oort, E., 2015. “Frictional pressure loss of drilling fluids in a fully eccentric annulus”. *Journal of Natural Gas Science and Engineering*, Vol. 26, pp. 1119–1129.

Erge, O., Ozbayoglu, M.E., Miska, S.Z., Yu, M., Takach, N., Saasen, A. and May, R., 2014. “Effect of Drillstring Deflection and Rotary Speed on Annular Frictional Pressure Losses”. *Journal of Energy Resources Technology*, Vol. 136, No. December, pp. 042909–1–042909–10.

Fang, P., Manglik, R. and Jog, M., 1999. “Characteristics of laminar viscous shear-thinning fluid flows in eccentric annular channels”. *Journal of Non-Newtonian Fluid Mechanics*, Vol. 84, No. 1, pp. 1–17.

GhasemiKafrudi, E. and Hashemabadi, S., 2016. “Numerical study on cuttings transport in vertical wells with eccentric drillpipe”. *Journal of Petroleum Science and Engineering*, Vol. 140, pp. 85–96.

Khataniar, S., Chukwu, G.A. and Xu, H., 1994. “Evaluation of rheological models and application to flow regime determination”. *Journal of Petroleum Science and Engineering*, Vol. 11, No. 2, pp. 155–164.

Lídio, M.S. and Siqueira, R.N., 2015. "Drill pipe eccentricity effects on horizontal wells cleaning process". In *Proceedings of the 23rd ABCM International Congress of Mechanical Engineering*. ABCM, Rio de Janeiro, Brazil.

Madlener, K., Frey, B. and Ciezki, H.K., 2009. "Generalized reynolds number for non-newtonian fluids". *Progress in Propulsion Physics*, Vol. 1, pp. 237–250.

Mingzhong, L., Ruihe, W., Chengwen, W., Qun, F. and Yongbo, X., 2013. "Study on Flow Characteristic of Non-Newtonian fluid in Eccentric Annulus". *Journal of Applied Sciences, Enginnereing and Technology*, Vol. 6, No. 13, pp. 2451–2458.

Nouar, C., Desaubry, C. and Zenaidi, H., 1998. "Numerical and experimental investigation of thermal convection for a thermodependent Herschel-Bulkley fluid in an annular duct with rotating inner cylinder". *European Journal of Mechanics - B/Fluids*, Vol. 17, No. 6, pp. 875–900.

Ofei, T.N., Irawan, S., Pao, W. and Osgouie, R.E., 2015. "Modified yield power-law fluid flow in narrow annuli with inner rotating pipe". the canadian journal of chemical engineering". *The Canadian Journal of Chemical Engineering*, Vol. 93, pp. 150–165.

Ogugbue, C.C. and Shah, S.N., 2012. "CFD modeling of non-newtonian flow in eccentric annular geometries.PDF". *International Journal of Petroleum Engineering*, Vol. 6, No. 1, pp. 9–34.

Ooms, G. and Burgercentrum, J.T., 1999. "Influence of drillpipe rotation and eccentricity on pressure drop over borehole during drilling". In *Proceedings of the SPE Annual Technical Conference and Exhibition*. SPE, Houston, USA.

Sorgun, M., Aydin, I. and Ozbayoglu, M.E., 2011. "Friction factors for hydraulic calculations considering presence of cuttings and pipe rotation in horizontal/highly-inclined wellbores". *Journal of Petroleum Science and Engineering*, Vol. 78, pp. 407–414.

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., 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, No. 4, pp. 829–838.

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