EFFECTS OF DIAMETERS RATIO ON THE EFFICIENCY OF CLEANING PROCESS IN HORIZONTAL WELLS

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Abstract: *The oil and gas extraction is a process in fully development, needing always new technological advances to keep up with the problems encountered. In horizontal wells drilling, an efficient removal of cuttings from the formation is very important and the main function of the drilling fluid is the continuous removal of the cuttings generated by the drill. Various parameters affect the performance of the drilling process, which include: the geometry of the wellbore, the drill pipe rotation, the axial flow rate and the rheology of the drilling fluid. This study is concerned with the geometry factor, with the objective of evaluating the influence of the diameters ratio (κ) on the cleaning process of horizontal wells. The diameters ratio is defined as the ratio between the drill pipe and wellbore diameters. For this study, Ansys CFX 16.0 was used, with a fluid characterized by the Herschel-Bulkley model, with specific mass ρ = 1000 kg/m^3, yield stress τ_0 = 17.81 Pa, consistency index K = 0.26 Pa.s^n and flow behavior index n = 0.74. The geometry is defined by an annular space 2.5 meters long, with variable eccentricity, inner diameter fixed at 50.8 mm and outer diameter determined by the diameters ratio (κ). Five diameters ratios were analyzed, varying from 0.5 to 0.9. The process parameters used are: Reynolds numbers (Re) of 200, 600 and 1000; drill pipe rotations (ω) of 0, 200 and 400 rpm and eccentricities (ε) of 0, 0.4 and 0.8. The increase of the diameters ratio causes an increment in the axial velocity, enhance the rotational effects, decrease the effective viscosity and increase the pressure loss. The understanding of the effects of diameters ratio on flow behavior is very important in order to obtain parameters to improve the efficiency of the horizontal wells cleaning process.*

Keywords: *Diameters ratio, CFD, horizontal wells, Herschel Bulkley.*

1. INTRODUCTION

Well drilling for oil and gas production is an activity in continuous development, always seeking new technologies to overcome the challenges encountered in the process. A major difficulty in this process is to find a good cleaning strategy, avoiding problems such as obstruction of the annular space or blockage the drill string, and consequently, the loss of the well.

The drilling fluid has several functions in the well drilling process, like: ensure the well's integrity, cool and lubricate the drill bit, and also to keep the hydrostatic pressure on the formation to prevent fluid invasion (kick). But the main function is still the removal of cuttings generated during the process (Caenn and Chillingar, 1996; Caenn *et al.*, 2014). There are several models that can predict the rheological behavior of these fluids. Works like Haciislamoglu and Langlinais (1990), Kelessidis *et al.* (2006), Founargiotakis *et al.* (2008), Kelessidis *et al.* (2011), Ofei *et al.* (2015) and Erge *et al.* (2015) use the Herschel-Bulkley model.

Cuttings transport and removal is influenced by several parameters, among them, we can mention the geometry, rheology of the drilling fluid, rotation and eccentricity of the drill string, axial flow rate and cuttings characteristics (Loureiro and Siqueira, 2006; Sun *et al.*, 2014; Vieira Neto *et al.*, 2014; Tardy and Bittleston, 2015; Lídio and Siqueira, 2015b; Zanete and Siqueira, 2015; Gabriel and Siqueira, 2015).

Ofei *et al.* (2014) used computational fluid dynamics (CFD) to evaluate the effects of diameters ratio (ratio between drill pipe and wellbore diameters), axial velocity, rheology of the fluid and drill pipe rotation, and cuttings concentration on pressure drop in horizontal wells. Concerning the geometry of the well, the authors concluded that the increased diameters ratio reduces the concentration of particles, but increases the pressure drop.

Ofei *et al.* (2015) also used a CFD code to evaluate the influence of diameters ratio, eccentricity and drill pipe rotation on flow patterns and pressure drop of Herschel - Bulkley fluids in annular spaces. Increasing the diameters ratio increases pressure drop along the flow and, in cases where there is no rotation of the inner cylinder, it provides an increased axial velocity.

Erge *et al.* (2015), on a theoretical and experimental study, evaluated the influence of diameters ratio, eccentricity and drilling fluids properties on the transition from the laminar to turbulent regime in Yield Power Law fluid flows. The increase in diameters ratio increases the critical Reynolds number, mainly for low values of behavior index.

Although several studies evaluates the influence of diameters ratio in annular flows, the subject is still not conclusive. The objective of this study is to use computational fluid dynamics to evaluate the influence of diameters ratio on the efficiency of horizontal wells cleaning process, for a laminar flow where the drilling fluid is characterized by the Herschel-Bulkley rheological model.

2. BASIC EQUATIONS

For a steady state isothermal flow, the governing equations are continuity, Eq. (1), and Navier-Stokes equation, Eq. (2).

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

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

In these equations , P is pressure, g is gravity acceleration, V is the flow velocity , ρ is specific mass and μ is the fluid viscosity.

2.1 Rheological Model and Flow Regime

The drilling fluid is characterized by the Herschel-Bulkley model. This model has three parameters, being simpler than the Cross model and, at the same time, it is more accurate than the Power- Law model. According to Chhabra and Richardson (2008) the behavior of this fluid is described by Eq. (3).

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

In this equation, τ is the shear stress, τ_0 is the yield stress, K is the consistency index, n behavior index and $\dot{\gamma}$ is the shear rate.

To ensure laminar flow conditions, the Reynolds numbers below the transition threshold were used. Madlener *et al.* (2011) presents a relationship to calculate the Generalized Reynolds Number, defined by Eq. (4).

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

In the above equation, $\bar{u}$ is the bulk flow velocity, the local shear rate (m) is defined by Eq. (5) and the hydraulic diameter (D_h) by Eq.(6), where D_i and D_o are the drill pipe and wellbore diameters, respectively.

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

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

2.2 Transport Capacity

According to Chhabra and Richardson (2008), the non-dimensional axial velocity profile for pseudo-plastic fluids has a central region with little velocity variation, corresponding to a region of high effective viscosity. High velocity and viscosity combined contribute to the cuttings transport.

According to Pereira (2006), in eccentric annular regions, the particles tend to be transported in the larger gap (sector A), due to core flow effect. Based on this, it was created a dimensionless parameter called transport capacity (η) defined as the product of the dimensionless length of the central region by the bulk velocity in this region, also dimensionless. Cases with higher values of η, possibly, has a greater potential for cuttings transport.

Figure 1 shows the non-dimensional axial velocity profile, displaying the central region length (L) and the average velocity in this region $(u/U)_{avg}$. It also shows the transport capacity (η) parameter definition. The velocity data are taken at a section located at 2 m from the inlet.

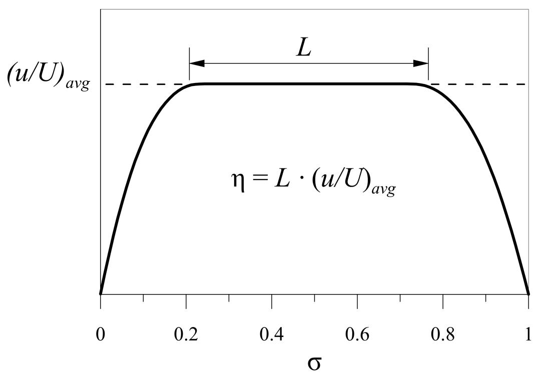

Figure 1: **Schematic representation of the transport capacity parameter**

3. METODOLOGY

3.1 Geometries

The geometry consists of a horizontal annulus formed by the drill column (inner cylinder) and the wellbore wall (outer cylinder) with 2.5 m length, which is long enough to the flow development. Concentric and eccentric configurations were evaluated. Figure 2 shows a schematic cross-section of the analyzed geometry, including the upper (A), right (B), lower (C) and left (D) sectors.

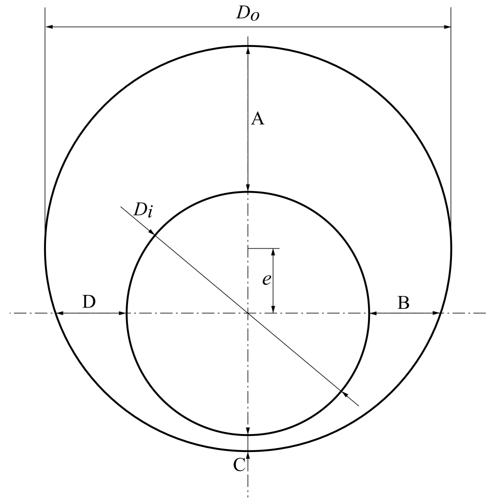

Figure 2: **Schematic representation of the wellbore cross-section.**

The drill column position is determined by the eccentricity (ε), which is the ratio between twice the distance between centers (e) and the difference of diameters (D_o - D_i).

The inner diameter (D_i) is set to 50.8 mm (2 in) and the outside diameter (D_o) is determined by the ratio of diameters (κ). Figure 3 shows the five diameters ratios evaluated in this work.

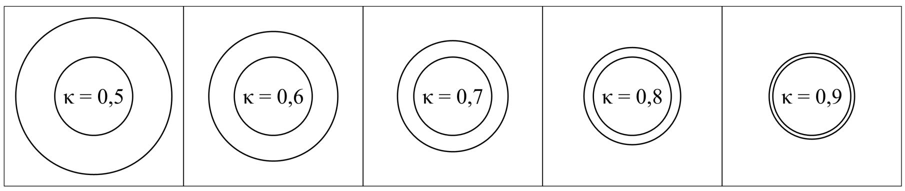

Figure 3: **Geometries evaluated according to the diameters ratio** (κ)

3.2 Process Parameters

The fluid used in this work is characterized by the Herschel-Bulkley model, having its properties based on a standard drilling fluid, used by a large national oil company according to Pereira (2013). The fluid has density ρ = 1000 kg/m^3, yield stress τ_0 = 17.81 Pa.s, consistency index K = 0.26 Pa.s^n and behavior index n = 0.74.

Table 1 shows the process parameters evaluate for each diameters ratio.

Table 1: **Process parameters**

Reynolds number (Re)	Column Rotation (ω) - RPM	Eccentricity (ε)
200	0	0
600	200	0.4
1000	400	0.8

3.3 Mesh

The grid independence test was performed with the most critical condition, e = 0.8, ω = 400 RPM and Re = 1000. The independence of the results was obtained by a structured mesh with 108 elements in the axial direction, 90 elements in the radial direction and 220 elements in the azimuthal direction.

4. RESULTS

4.1 Model Validation

The model was used to simulate the experiments carried out by Nouar *et al.* (1998) and the results of the simulation was compared with the experimental data and a good agreement was observed. Figure 4 shows the non-dimensional axial velocity profiles for both cases (experimental and simulated). The proposed model showed an error of 1% for the maximum velocity and 0.61% for the mean velocity.

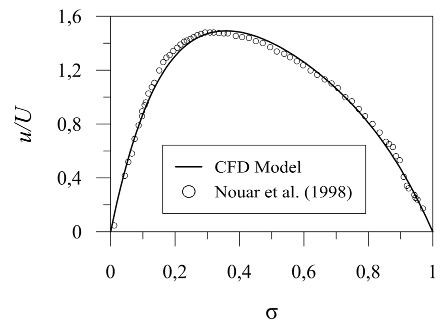

Figure 4: **Comparison of simulated non-dimensional axial velocity and the experimental data of Nouar *et al.* (1998).**

4.2 Tangential Velocities

Figure 5a shows the influence of the diameters ratio on non-dimensional tangential velocity profiles in the concentric annulus. In this case, the profile is axisymmetric. For the most eccentric case evaluated (ε = 0.8), the profiles change along the sectors, Figs. 5b and 5c show the profiles for the sectors A (top) and C (bottom).

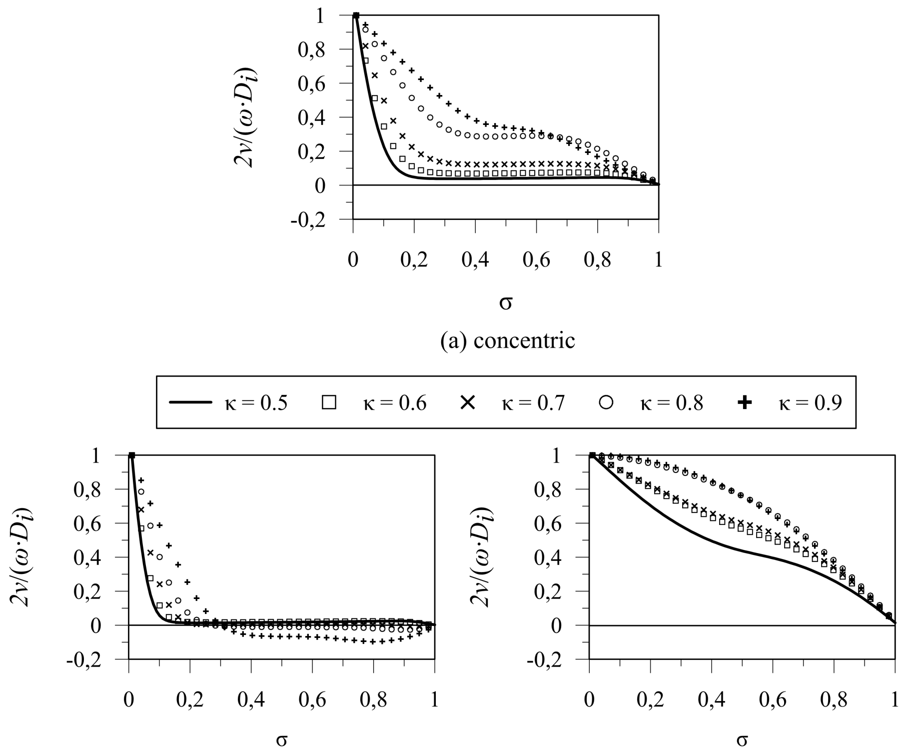

Figure 5: **Influência da razão de diâmetros (κ) sobre a velocidade tangencial**.

In Fig. 5 the Reynolds number is set to 200, because for higher values of Re there is a reduction of the influence of the diameters ratio on tangential velocity. The rotation of the drill string is ω = 400 RPM, because there is little variation between the non-dimensional profiles for the rotation of 200 RPM.

The increase of the diameters ratio tends to increase the tangential velocity profile in the central region for the concentric case (Fig. 5a). The increase of tangential velocity, as well as the velocity gradients, assists in gravel resuspension, which is transported by the axial flow. Both parameters increase the shear stress on the gravel bed, favoring its resuspension, as indicated by Loureiro and Siqueira (2006).

The most critical eccentricity case was analyzed because the intermediate eccentricity (0.4) shows little changes in the tangential velocity profiles when compared to concentric case. In Fig. 5b, Sector A (higher), it is possible to observe that, for low diameters ratio values (κ = 0.5), the column rotation affects the profiles up to σ = 0.1, from this value onwards the tangential velocity is equal to 0. With the increase of κ, negative tangential velocities begins to appear after σ = 0.2, which can be explained by the presence of vortices. Similar results were obtained by Vieira Neto *et al.* (2014).

In Fig. 5c, sector C (bottom), it is possible to observe that the increase in the value of κ provides an increase in the tangential velocities. In horizontal wells, the particles tend to deposit in the lower region of the annular and increased tangential velocity in this region effectively contributes to the cleaning process, assisting in the resuspension of sedimented particles as concluded by Lídio and Siqueira (2015a).

4.3 Axial Velocity

Figure 6 shows the axial velocity contours for different diameters ratio in the most critical case analyzed, ε = 0.8, Re = 1,000 and ω = 400 RPM, showing that the increase of κ provides an increase in the non-dimensional axial velocity. For all other cases, similar results were obtained, i.e., the increase of κ increases the axial velocity, as indicated by Ofei *et al.* (2015).

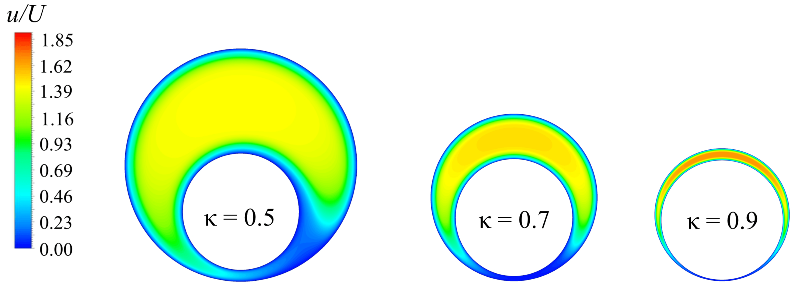

Figure 6: **Influence of diameters ratio (κ) on axial velocity contours**.

4.3.1 Transport Capacity

The increase of axial velocity has a positive effect on the well cleaning process but other parameters also contributes to this process. For example, a high axial velocity region associated with a high effective viscosity contributes better to the transport of the particles suspended in the flow. The transport capacity (η) allows a better understanding of the cuttings transport behavior. Figure 7 shows the influence of diameters ratio on the transport capacity.

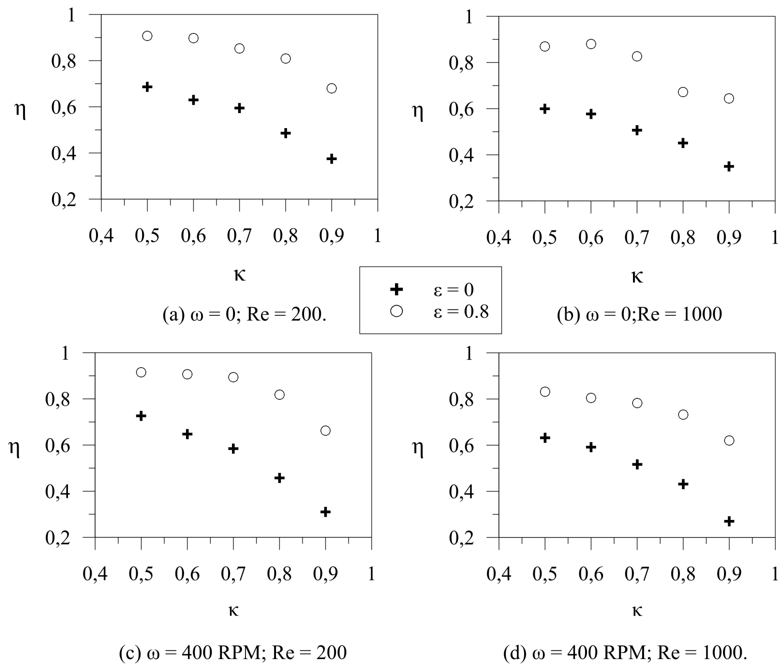

Figure 7: **Influence of diameters ratio (κ) on transport capacity (η)**.

According to Fig. 7, it is possible to notice that the transport capacity suffers little variation for $0.5 \leq \kappa \leq 0.7$, with larger variations for $0.8 \leq \kappa \leq 0.9$. This reduction of the transport capacity can reach more than 50% with the increase in κ values for the concentric cases with ω = 400 RPM (Fig. 7c).

Figure 7 also shows that, in all analyzed cases, the transport capacity is higher for the eccentric annulus. In such cases, the flow takes place mainly in the upper region of the annular space, providing higher velocities in this sector. The large values of η for the eccentric cases are positive for the cleaning process since, due to the core-flow effect, the particles tend to be transported by the flow in the upper sector (A) as indicated by Pereira (2006).

4.4 Pressure Drop

Figure 8 shows the influence of the diameters ratio, associated with the rotation of the drill string, on pressure drop for the concentric (ε = 0) and eccentric (ε = 0.8) cases.

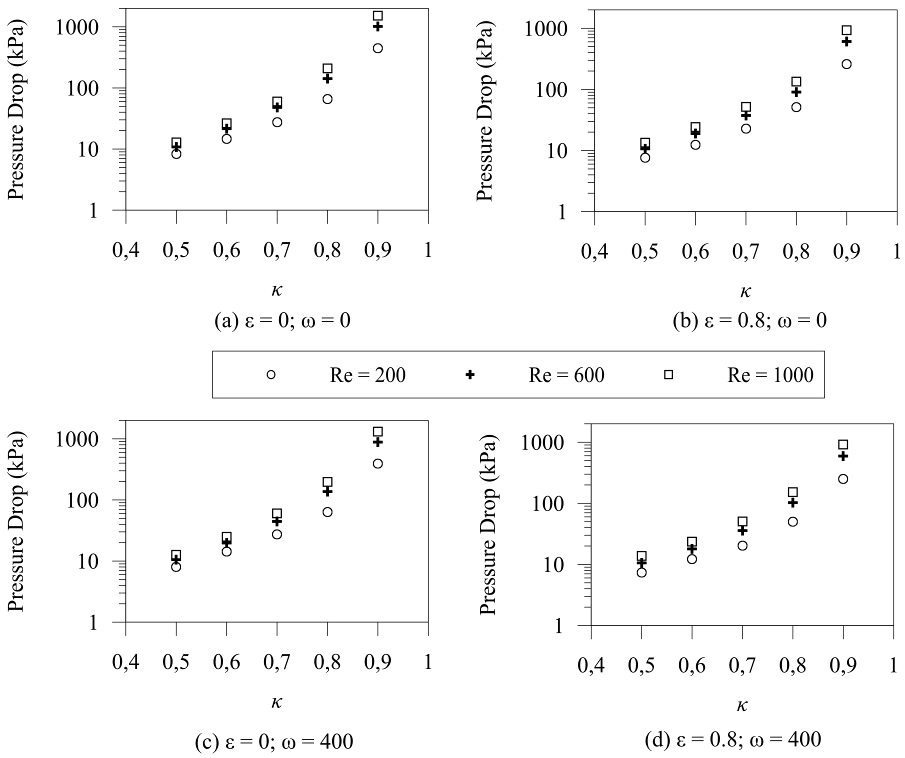

Figure 8: **Influence of diameters ratio (κ) on pressure drop**.

The data obtained in this study agrees with the literature data, that is, increasing the diameters ratio increases the pressure drop, mainly for κ = 0.9 (Fig. 8). The increased in pressure drop was also observed by Erge *et al.* (2015) and Ofei *et al.* (2014), moreover, high a pressure drop may be detrimental to the well drilling process, particularly where there is a narrow margin between the pore pressure gradients and formation fracture.

In Fig. 8, it is possible to observe that the increase in the Reynolds number enhances the effect of the diameters ratio on pressure drop, further increasing these values. The eccentricity reduces the effects of κ on pressure drop, particularly for high values of Reynolds number. The rotation of the drill string has little influence on the pressure drop, but its increase reduces the pressure drop, particularly in the concentric cases.

5. CONCLUSIONS

The increased diameters ratio provides a considerable increase in the pressure drop along the wellbore and requires a greater energy consumption. This increase in pressure drop can be detrimental to well drilling process, particularly where there is a narrow margin between the pore pressure gradient and fracture of the formation. If the pressure in the wellbore exceeds these values, it may occur a loss of circulation of the drilling fluid, i.e., the fluid is lost to the formation, which may cause environmental damages.

The increase in diameters ratio provides increased tangential velocity as well as velocity gradients, assisting in the resuspension of the cuttings to be transported by the axial flow.

In eccentric cases, the increase of κ provides negative tangential velocities in sector A from σ = 0.2 onwards, which can be explained by the presence of vortices. In horizontal wells, the cuttings particles tend to sediment on the bottom of the annular space and with the increase in the diameters ratio there is an increase in tangential velocities in the lower sector, improving the resuspension of sedimented particles and therefore, the well cleaning process.

The increase in the diameters ratio also resulted in an increase in the axial flow velocity for all analyzed cases, following the results presented in previous works. By contrast, the increase of κ provides a reduction in the transport capacity η.

The transport capacity is higher for the eccentric case with low values of κ and Re. In such cases the flow takes place mainly in the upper region of the annular space, thus providing higher velocities in this sector. The large value of η for the eccentric cases are positive for the well-cleaning process. Due to the effect of core-flow, the particles tend to be carried by the flow in the upper sector (A).

Therefore, we conclude that the well drilling process with lower diameters ratios leads to a lower pressure drop, reducing the risks to the formation. Moreover, it presents higher values of transport capacity. On the other hand, wells with higher values of κ have higher tangential velocities, in the cases with rotation of the column, thereby maintaining the particles in suspension and promoting the erosion of sedimented bed.

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.

Caenn, R., Darley, H. and Gray, G., 2014. *Fluidos de Perfuração e Completação*. Elsevier, Rio de Janeiro, 1st edition. ISBN 9788535269512.

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

Erge, O., Ozbayoglu, E.M., Miska, S.Z., Yu, M., Takach, N., Saasen, A. and May, R., 2015. "Journal of Petroleum Science and Engineering Laminar to turbulent transition of yield power law fl uids in annuli". *Journal of Petroleum Science and Engineering*, Vol. 128, pp. 128–139.

Founargiotakis, K., Kelessidis, V.C. and Maglione, R., 2008. "Flow of Herschel – Bulkley Fluids in". *The Canadian Journal of Chemical Engineering*, Vol. 86, pp. 676–683.

Gabriel, A.C. and Siqueira, R.N., 2015. "Influência do índice de comportamento do modelo power law na eficiência do processo de perfuraão". In *Anais do VI Encontro Nacional de Hidráulica e Perfuração de Poços de Petróleo e Gás*. Rio Quente, Brasil.

Haciislamoglu, M. and Langlinais, J., 1990. "Non-Newtonian Flow in Eccentric Annuli". *Journal of Energy Resources Technology*, Vol. 112, pp. 3–9.

Kelessidis, V.C., Maglione, R., Tsamantaki, C. and Aspirtakis, Y., 2006. "Optimal determination of rheological parameters for Herschel – Bulkley drilling fluids and impact on pressure drop , velocity profiles and penetration rates during drilling". *Journal of Petroleum Science and Engineering*, Vol. 53, pp. 203–224.

Kelessidis, V.C., Dalamarinis, P. and Maglione, R., 2011. "Experimental study and predictions of pressure losses of fluids modeled as Herschel–Bulkley in concentric and eccentric annuli in laminar, transitional and turbulent flows". *Journal of Petroleum Science and Engineering*, Vol. 77, pp. 305–312.

Lídio, M.S. and Siqueira, R.N., 2015a. "Drill Pipe Eccentricity effects on horizontal wells". In *23rd ABCM International Congress of Mechanical Engineering*. Rio de Janeiro, Brazil.

Lídio, M.S. and Siqueira, R.N., 2015b. "Efeitos da rotação da coluna no escoamento de fluidos não-newtonianos em anulares excêntricos". In *Anais do VI Encontro Nacional de Hidráulica e Perfuração de Poços de Petróleo e Gás*. Rio Quente, Brasil.

Loureiro, B.V. and Siqueira, R.N., 2006. "Determinação da tensão de cisalhamento mínima para arraste de partículas em um leito". In *11th Brazilian Congress of Thermal Sciences and Engineering – ENCIT 2006*. Curitiba, Brasil.

Madlener, K., Frey, B. and Ciezki, H.K., 2011. "Generalized reynolds number for non-newtonian fluids". *Progress in Propulsion Physics*, Vol. 1, pp. 237–250.

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, pp. 875–900.

Ofei, T.N., Irawan, S. and Pao, W., 2014. "CFD Method for Predicting Annular Pressure Losses and Cuttings Concentration in Eccentric Horizontal Wells". *Journal of Petroleum Engineering*.

Ofei, T.N., Irawan, S., Pao, W. and Osgouei, R.E., 2015. "Modified Yield Power-Law fluid flow in narrow annuli with inner rotating pipe". *The Canadian Journal of Chemical Engineering*, Vol. 93, pp. 150–165.

Pereira, F.A.R., 2006. *Escoamento laminar de líquidos não-newtonianos em seções anulares: estudos de CFD e abordagem experimental.* Doutorado, Universidade Federal de Uberlândia.

Pereira, M.S., 2013. *Aplicação de secagem por microondas no tratamento de cascalho de perfuração*. Doutorado, Universidade Federal de Uberlândia.

Sun, X., Wang, K. and Yan, T., 2014. "Effect of drillpipe rotation on cuttings transport using computational fluid dynamics (CFD) in complex structure wells".

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 nonnewtonian fluids in concentric and eccentric annuli”. *Brazilian Journal of Chemical Engineering*, Vol. 31, pp. 829–838. doi:10.1590/0104-6632.20140314s00002871.

Zanete, H.Z. and Siqueira, R.N., 2015. “Escoamento axial de fluidos não-newtonianos em anulares excêntricos com rotação do cilindro interno”. In *Anais do VI Encontro Nacional de Hidráulica e Perfuração de Poços de Petróleo e Gás*. Rio Quente, Brasil.

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