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MULTIPHASE MODELLING OF DRILL PIPE ROTATION EFFECTS ON CUTTINGS TRASPORT IN HORIZONTAL WELLS

Ayrton Cavallini Zotelle

Renato do Nascimento Siqueira

João Henrique Sartori Vieira

Michel de Oliveira dos Santos

Instituto Federal do Espírito Santo, Department of Mechanical Engineering, São Mateus, Espírito Santo, Brazil.

ayrton.zotelle1@hotmail.com

renatons@ifes.edu.br

joaohsv_@hotmail.com

michel.santos@ifes.edu.br

Abstract. *One of the main problems in the horizontal wells drilling process is the cuttings transport mechanism through the annular. This study uses CFD multiphase flow to simulate and investigate the drill pipe rotation effects on pressure drop and cuttings transport inside of an eccentric annulus on horizontal wells. The drilling fluid has non-Newtonian behaviour, characterized by the Herschel-Bulkley rheological model, and the cuttings from the formation was simulated as spherical shape particles with 3 mm diameter. The results show that although the increase in the drill pipe rotation increases the pressure drop, it contributes to the removal of the particles from the wellbore, reducing the cutting concentration inside the annulus. The rotation displaces the particle bed in the direction of the rotation to the region of higher longitudinal velocities, improving the efficiency of the cleaning process.*

Keywords: *Multiphase flow, drill pipe rotation, cuttings transport, cleaning process, horizontal wells.*

1. INTRODUCTION

The extraction of oil and gas from reservoirs by the horizontal wells drilling method has been widespread within the petroleum industry. The method improves the performance of the process due to the increase of the contact area of the wellbore with the reservoir, allowing a better extraction of the hydrocarbons resources.

A fundamental issue in drilling horizontal wells is the mechanism of cuttings transport by the drilling fluid. Many factors, including the drill pipe rotation, particle size, rate of penetration, eccentricity and rheology, affect the ability of the drilling fluid to efficiently transport the cuttings to the surface and provide the cleaning of the well. An inefficient particle transport on horizontal wells can form a cuttings bed in the lower region of the annular, allowing the drill pipe obstruction, impairing the drilling process.

Some authors investigated the drill pipe rotation effects on non-Newtonian fluids flow in eccentric annulus by the CFD method in a single-phase model, without the cuttings addition. Their studies have shown that the increase of the drill pipe rotation causes an increase of the pressure drop (Lídio and Siqueira, 2015; Furini and Siqueira, 2017). In a single-phase flow, the effects of flow resistance and change of the flow pattern of the drilling fluid offered by the cuttings presence during the drilling process are not evaluated.

Recently, the cuttings transport behaviour on drilling wells was investigated using the Computational Fluid Dynamics method (Facuri, 2014; Heydari et al., 2015; Akhshik et al., 2015). Results of the studies indicate that the increase in the particle size reduces the rate of cuttings transport. An increase of the cuttings size increases the gravitational force, diminishing the transport of the particles in the annulus (Pang et al., 2018).

The cleaning process on horizontal wells was studied by experimental method using different fluids characterized by the Bingham Plastic rheological model (Yu et al., 2007). It was noted that the rheological parameters of the drilling fluid have significant effects on cuttings transport efficiency. The rate of cuttings transport increase as the drilling fluid viscosity increase.

Some studies show that the multiphase CFD model is efficient to describe the particles behaviour inside the annular (Facuri, 2014; Heydari et al., 2015; Pang et al., 2018). The parameters that influence the efficiency of the cleaning process were investigated for Bingham Plastic fluids using the multiphase flow model. They show that the drill pipe rotation has a significant influence on the cuttings transport. In contrast, the fluid flow has little effect on the cuttings concentration on the annular, although it is the principal responsible for the increase of the pressure drop.

Besides the various studies found in the literature about the parameter that influence the drilling process, the effects of these parameters on the cuttings cleaning process should be better evaluated. Therefore, the present work investigates, by the CFD multiphase modelling, the drill pipe rotation effects on the pressure drop and the efficiency of the cleaning process in an eccentric annulus using pseudo-plastic fluids.

2. METHODOLOGY

2.1 Multiphase model and governing equations

The Euler-Euler Granular multiphase model was used to represent the solid-liquid interactions in the flow. In this model both phases are considered as interpenetrating. The cuttings are treated as a dispersed solid and the drilling fluid is treated as a continuous fluid, thus introducing the concept of volumetric fraction and the momentum and continuity equations are solved for each phase.

The continuity equation for the fluid phase is expressed as:

$$\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l v_l) = 0 \quad (1)$$

Where α_l , v_l and ρ_l are the volume fraction, velocity vector and the density of the fluid phase, respectively. The moment conservation equation for the fluid phase is given as:

$$\frac{\partial}{\partial t}(\alpha_l \rho_l v_l) + \nabla \cdot (\alpha_l \rho_l v_l v_l) = \alpha_l \nabla \cdot \tau_l + \alpha_l \rho_l g - \alpha_l \nabla P - \beta(v_l - v_s) \quad (2)$$

Where g is the acceleration of gravity, β is the drag coefficient between the phases, v_l is the solid phase velocity vector, ∇P is the pressure gradient and τ_l is the stress tensor of liquid. The mass conservation equation for solid phase is expressed as:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s v_s) = 0 \quad (3)$$

The moment conservation equation for the solid phase is given by:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s v_s) + \nabla \cdot (\alpha_s \rho_s v_s v_s) = -\alpha_s \nabla P + \nabla P_s + \alpha_s \nabla \cdot \tau_s + \alpha_s \rho_s g + \beta(v_l - v_s) \quad (4)$$

Where τ_s is the stress tensor of solid phase and P_s is the solid pressure. To verify the changes of increase the drill pipe rotation on the flow pattern and the effects of this parameter on the cleaning process, some dimensionless parameters were used. The dimensionless axial velocity was defined as:

$$W_{DL} = \frac{w\pi(D_e^2 - D_i^2)}{4Q_{inlet}} \quad (5)$$

Where D_e and D_i are the external diameter and internal diameter, respectively, Q_{inlet} is the inlet flow rate and w is the axial velocity on the position. The dimensionless distance of the inner cylinder is expressed as:

$$S = \frac{y - y_i}{y_e - y_i} \quad (6)$$

Where y is the relative Y-coordinate, y_e is the position of the external circle and y_i is the position of the inner diameter. Therefore, $S = 0$ represents the position of the drill pipe and $S = 1$ represents the position of the wellbore. The cleaning efficiency is calculated as:

$$\eta = 1 - \frac{m_c}{m_t} \quad (7)$$

Where m_c is the cuttings mass inside the section, m_t is the total mass of the section. To evaluate the increase of the cleaning efficiency and the energy necessary to the process on the six cases evaluated, a relation of this parameters was proposed as:

$$R_i = \left(\frac{\eta_{i+1} - \eta_i}{U_{i+1} - U_i} \right) \times 100 \quad (8)$$

Where i and $i+1$ are the index that represents the different levels of rotation evaluated. The lowest rotational speed receives the index 1, while the highest rotation level receives the index 6.

2.2 Phase interaction and solution parameters

The specifications of the phase interactions, granular phase parameters and the solution method parameters used in this paper are showed in Table 1.

Table 1. Simulation parameters used in this paper.

			Reference	
Phase interaction	Drag model	Gidaspow	(Heydari et al., 2015)	
	Lift model	Saffman-mei		
	Restitution coefficient	0.9	(Akhshik et al., 2015)	
Granular phase parameters	Diameter	3 mm	(Pang et al., 2018)	
	Granular viscosity	Gidaspow	(Facuri, 2014)	
	Granular bulk viscosity	Lun et. al.		
	Frictional viscosity	Johnson et. al.	(Heydari et al., 2015)	
	Frictional pressure	Based-KTGF	(Facuri, 2014)	
	Frictional modulus	Derived		
	Frictional packing limit	0.61	-	
	Granular temperature	Algebraic	(Facuri, 2014)	
	Solids pressure	Lun et. al.		
	Radial distribution	Lun et. al.		
	Elasticity modulus	Derived		
	Packing limit	0.63		
Solution method	Time step	0.01 s	-	
	Pressure-Velocity coupling	SIMPLE	-	
	Spatial Discretization	Gradient	Least Squares Cell Based	-
		Momentum	Second Order Upwind	(Facuri, 2014)
		Volume fraction	QUICK	
	Transient Formulation	Second Order Implicit		

2.3 Boundary conditions and phases properties

For the realization of the numerical simulation, Ansys FLUENT® software version 16.0 was used. The drilling fluid, with density $\rho_f = 1000 \text{ kg/m}^3$, presented non-Newtonian behaviour, characterized by the Herschel-Bulkley rheological model, with yield stress $\tau_0 = 17.81 \text{ Pa}$, consistency index $K = 0.26 \text{ Pa.s}^n$ and power-law index $n = 0.74$. Based on the analyses of Pang et al. (2018) and Yu et al. (2007), the cuttings from the formation was modeled with spherical shape, diameter 3 mm and density $\rho_c = 2610 \text{ kg/m}^3$.

Six numerical simulations were performed to investigate the drill pipe rotation effects on cleaning process and evaluate the effects of the changes on the operational parameters (pressure drop and torque on the drill pipe). For operational parameters, the drill pipe rotation values investigated varied from 0 to 100 rpm, anticlockwise, with 20 rpm steps, while the outer wall remained stationary. The drilling fluid flow rate was $22.7 \text{ m}^3/\text{h}$, ensuring the laminar flow regime, the rate of penetration (ROP) was kept constant 9.2 m/h (Yu et al., 2007) and the relative outlet pressure was considered 0 Pa. The gravitational force was enabled in the negative Y-coordinate.

Initially, the transient simulations were performed without the particles injection until the flow reached the steady state. The steady condition of the single-phase flow was considered the initial condition for the multiphase flow

simulation. The inlet pressure, as well as the cuttings mass inside the annulus was monitored during the simulations until stabilization, thus ensuring that the multiphase flow reached the steady state.

2.4 Geometry and computational mesh

The geometry used have length $L = 17.5$ m, with external diameter $D_e = 146.3$ mm, internal diameter $D_0 = 88.9$ mm and eccentricity $\varepsilon = 13.74$ mm (Yu et al., 2007). In the confection of the computational mesh it was considered that the minimum mesh size needs to be longer than the particle diameter. Therefore, the dimensional discretization was accomplished in order to compose a structural mesh with four radial divisions, sixty for tangential divisions and 350 axial divisions (Facuri, 2014), as shown in the Figure 1.

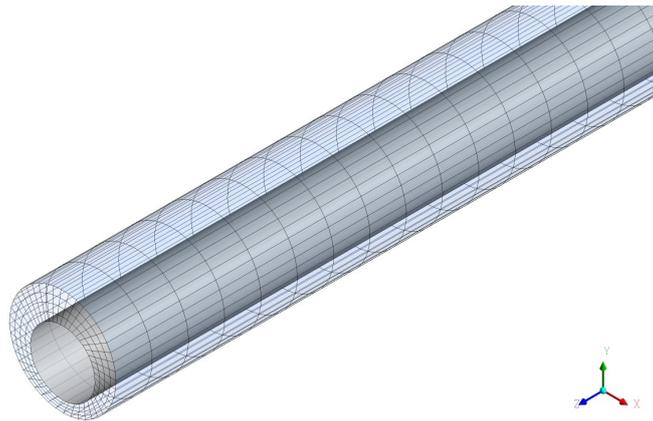


Figure 1. Geometry and mesh used.

3. RESULTS AND DISCUSSIONS

3.1 Model validation

The numerical model validation was aimed to verify the accuracy of the multiphase model. In order to perform the validation, the solid concentrations within the annular were compared between sections $Z = 8.8$ m and $Z = 15.4$ m for five previously selected cases performed in the experimental analysis of Yu et al. (2007). The drilling fluid used was fluid A described in the author's analysis. The operational parameters are listed in Table 2.

Table 2. Experimental cases performed by Yu. et al. (2007).

Case	Drill Pipe rotation [rpm]	Rate of Penetration [m/h]	Fluid flow [m ³ /h]
01	0	6.1	34.1
02	80	12.2	22.7
03	80	12.2	34.1
04	0	12.2	45.4
05	0	12.2	34.1

To prove the efficacy of the phase interaction parameters, like the granular model parameters, the results obtained by numerical simulations were also compared with the numerical analysis carried out by Facuri (2014). The results obtained for the selected cases are shown in the Fig 2.

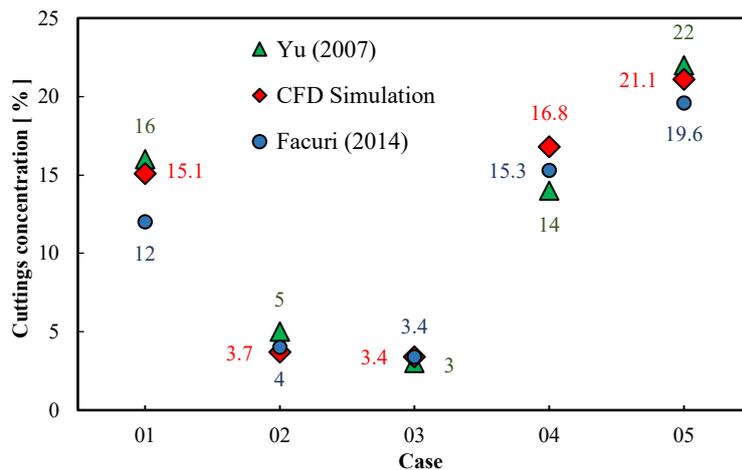


Figure 2. Cuttings concentration obtained on the model validation.

As shown in Figure 2, the numerical model results were satisfactory when compared to the results obtained by the experimental analysis, considering the complexity of the phenomenon. Thus, it was possible to verify the accuracy of the multiphase model selected to describe the physical phenomenon of the cleaning process. Based on this results, it was possible to note that, in most cases, the results were more accurate than those obtained in the numerical analysis of Facuri (2014), therefore, it's possible to conclude that the phase interaction models used in this paper were correctly selected.

3.2 Influence of drill pipe rotation on cuttings deposition

Figure 3 shows the deposition of cuttings through the wellbore at section Z = 12.2 m, where the multiphase flow is fully developed.

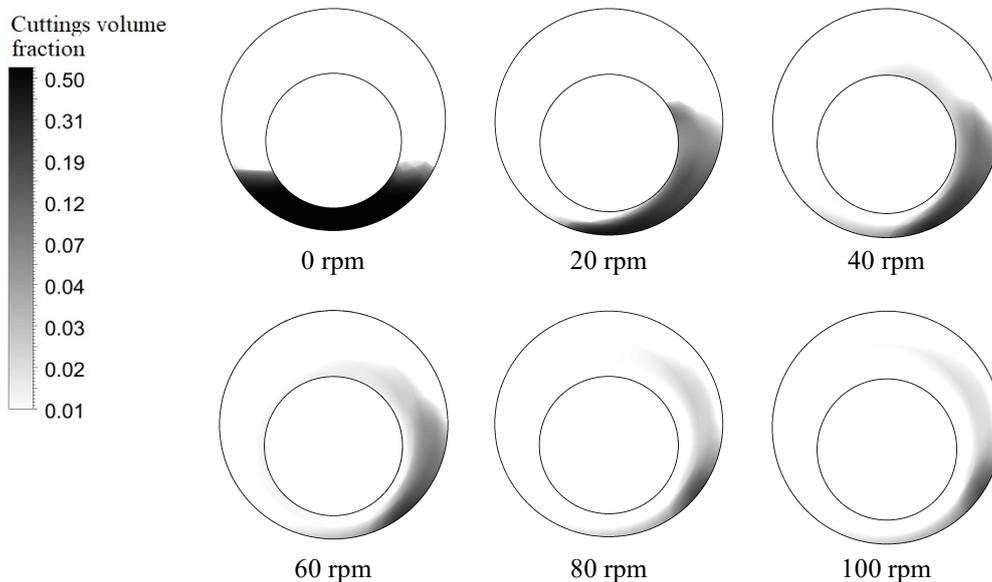


Figure 3. Contours of cuttings volume fraction for different rotations.

Due to the gravitational forces, the cuttings accumulate in the bottom region of the well, forming a static bed up to a specific height that the fluid velocity is so high that the cuttings cannot deposit. Fig. 3 shows that, without the rotational speed, the cuttings gradually accumulate, and the bed grows up to a specific height that the velocity of fluid flow reaches a critical value that the cuttings cannot deposit, and shows that the solid phase on the right side of the annulus is carried up with the intrusion of liquid phase. It is possible to note that, the drill pipe rotation has significant effects on

the rate of cuttings cleaning and, with the circumferential velocity, the solid-phase deposition bed is formed asymmetrically. The volume of cuttings decreases as the rotational velocity is intensified on the drill pipe. Figure 4 shows the quantitative values of solid volume in the fully developed region of the flow ($Z = 8.8 \text{ m}$ to 15.4 m).

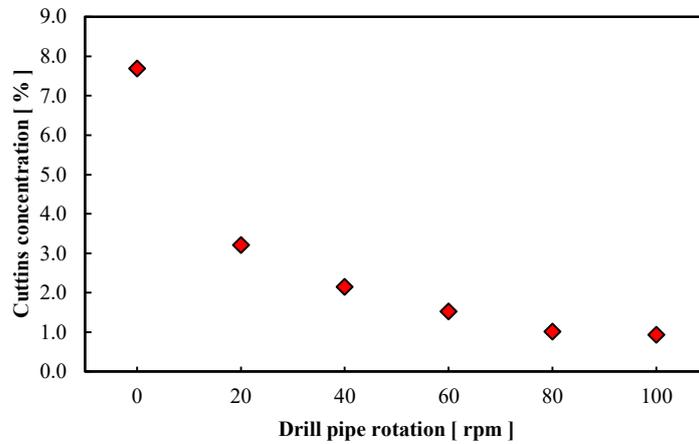


Figure 4. Cuttings volume inside the annular.

Figure 4 shows that the cutting concentration decreases significantly for rotating drill pipe in comparison with stationary drill pipe. On the figure, it is possible to verify that, for an efficient well cleaning process, it is not recommended to perform the process at low rotational speeds. It is noted that to perform the drilling process with low rotational velocities can increase the possibility of obstructing the drill pipe. As the rotational velocity increase, this effects on the cleaning process decrease, decreasing the difference between the cuttings concentration of one case and the former one.

3.3 Changes on the flow pattern

The main responsible for the cuttings transport the inside the wellbore are the drag and lift forces, which are directly related with the relative movement between the two phases. Therefore, the flow pattern of the drilling fluid is a potentiator of the cleaning process, thus an important parameter to be analyzed.

Figure 5 and 6 show the dimensionless axial and the tangential velocities of the drilling fluid on the bottom section of the annulus, while the dimensionless velocity for the top section is shown in Fig. 7.

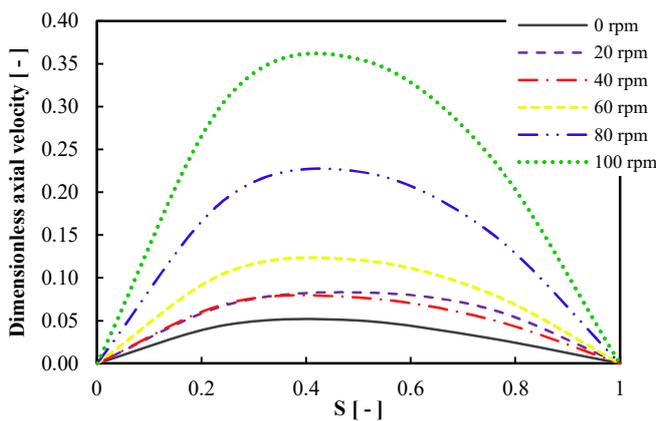


Figure 5. Axial velocity on the bottom section of the annular.

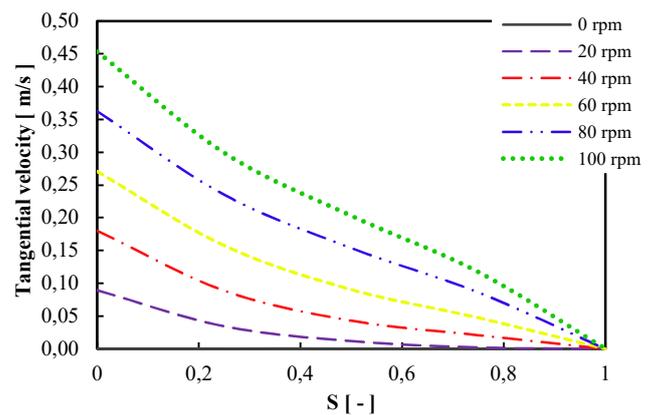


Figure 6. Tangential velocity on the bottom section of the annular.

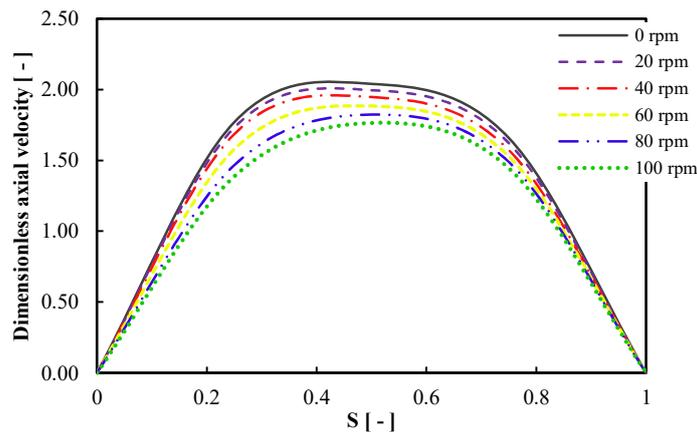


Figure 7. Axial velocity on the top section of the annulus.

It is possible to verify on Fig 5 and 7 that, the addition of rotation promotes an increase of the fluid flow velocity in the bottom section of the annulus, reducing the velocity on the top section. Figure 6 show that, increase the rotational speed increase the tangential velocity of the drilling fluid, elevating the cuttings to the highest fluid velocity region. As shown Fig. 3 and Fig. 4, the improve of velocity on the bottom section, besides the circumferential velocity, increases the drag and lift forces, increasing the rate of cuttings transport. The dimensionless axial velocity contours of the drilling fluid are shown in Fig. 8 for three of the six cases evaluated.

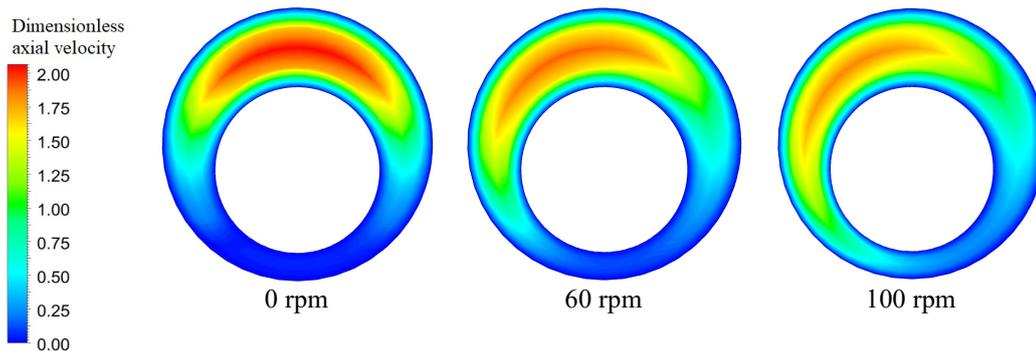


Figure 8. Axial velocity contour of drilling fluid.

The rotational velocity moves the highest fluid velocity zone on the rotational direction, distributing the flux on the bottom section. This effect was observed by Pereira et al. (2007) and Vieira Neto et al. (2014) and also by Lídio and Siqueira (2015).

3.4 Influence of rotational velocity on pressure drop and mechanical energy

To evaluate the energy needed for the drilling operation, two energy parcels were evaluated. The energy due to the pressure drop (parcel responsible for promoting the flow) and the energy due to the torque of the drill pipe (parcel responsible for the keep the pipe rotating at a certain velocity). Figure 9 shows the pressure drop per meter of length of the well, according to the rotations analyzed.

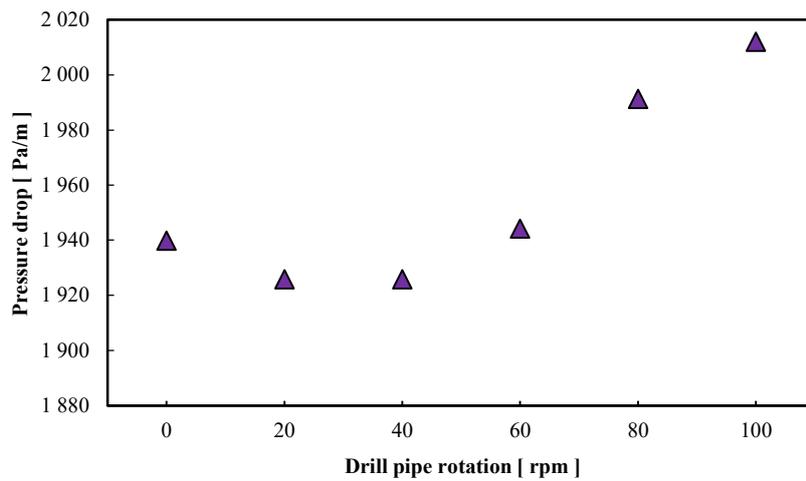


Figure 9. Pressure drop per meter as a function of the rotational speeds.

According to Figure 9, the pressure drop decreases, reaches a minimum and then increases with the increase of the rotation speed of the drill pipe. This phenomenon was identified by Pang et al. (2018). The increase of the tangential velocity makes the stationary cuttings bed to move on the rotational direction, reducing the obstruction of the low region of the well and thus decreasing the energy needed for the fluid to flow. With the removal of the stationary bed, the pressure drop tends to increase as the rotational velocity is intensified due to the increase of the wall shear stress.

The torque required to keep the drill pipe rotating, per meter of length on the fully developed region of the flow, is represented on Fig. 10.

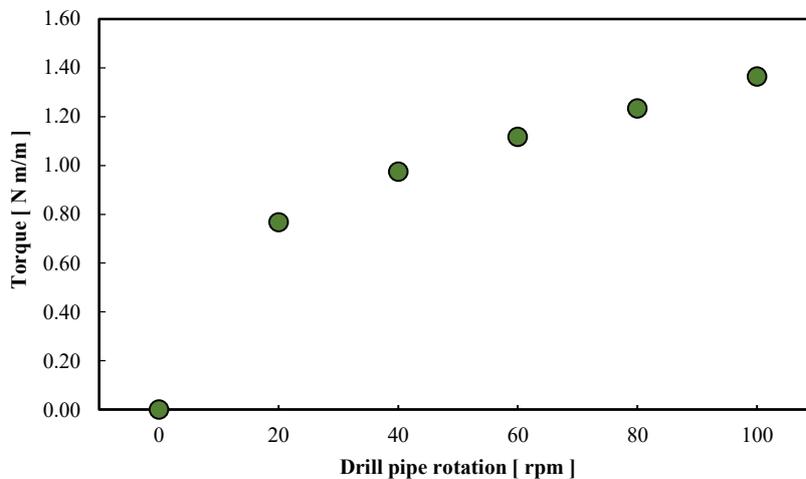


Figure 10. Torque per meter in function of the rotational velocity.

Fig. 10 shows that, the increase of the rotational speed promotes an increase of the torque to keep the drill pipe rotating. It is possible to note that the variation of the torque with the drill pipe rotation have a nonlinear behaviour. For low rotations of the drill pipe it is possible to note a greater difference in torque when compared to the difference at highest rotations.

To combine the pressure drop and the torque effects, the energy necessary to the process was described. The total mechanical energy was considered the sum of the parcel of energy by the pressure drop and the energy by the torque. Figure 11 shows the mechanical energy needed to the process to the cases evaluated per meter of well.

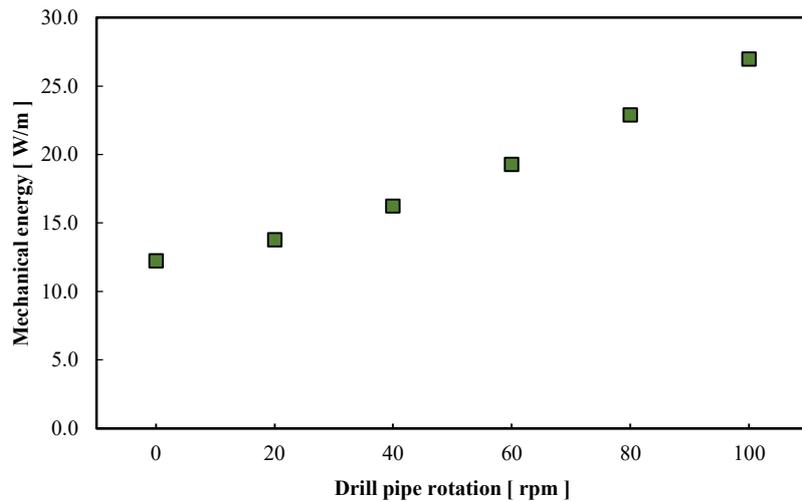


Figure 11. Mechanical energy per meter in function of the rotational velocity.

Figure 11 shows that the combined effects of the energy necessary to perform the process is increased as the rotational velocity increase. Although the energy parcels (torque and pressure drop), when evaluated separately, present a nonlinear behaviour, when the two parcels are combined, the energy have a linear behaviour as function of the rotation of the drill pipe.

Is possible to note that the rate of cuttings cleaning and the mechanical energy to perform the process varies with different proportions. To verify how much is efficient to increase the rotational velocity to increase the cleaning efficiency, the relation between the increase of cuttings cleaning and the mechanical energy was provided according the Eq. 8. Figure 12 shows the results obtained with the relation.

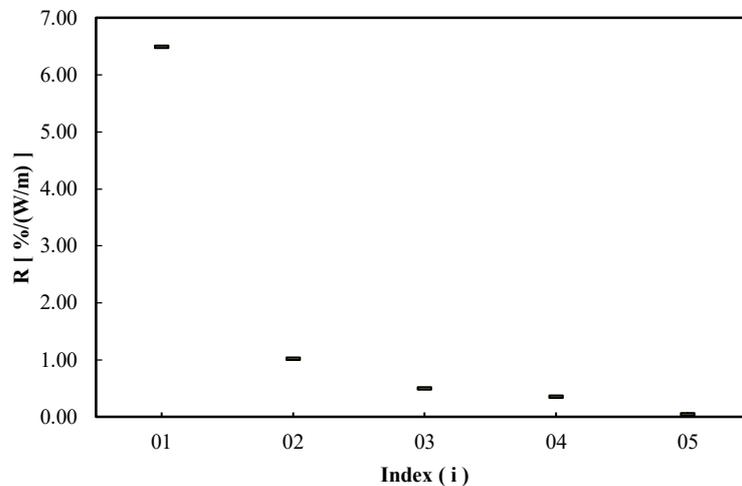


Figure 12. Rate of efficiency increase per unit of energy per meter.

The relation of the cleaning efficiency and the dispended mechanical energy decrease with the rotation, so, it is possible to verify that an excessive increase of the rotational velocity can promote a waste of energy, without change the cleaning process. This shows that, an incorrect selection of the operational parameters can increase the cost of the process or, in extremely cases, impairing the drilling process.

4. CONCLUSIONS

This research used a CFD methodology to evaluate the influence of the drill pipe rotation on the cleaning process and their effects on the pressure drop and mechanical energy necessary to the process. The results show that an increase in rotational velocity also increase cleaning rate. The rotational speed improves the flow on the bottom section of the annulus, increasing the drag force to perform the cleaning process and decreasing the volume of cuttings deposited on the interior of the wellbore. Without the drill pipe rotation, the cuttings bed is formed symmetrically, while increasing the rotational velocity the cuttings bed is formed asymmetrically. The pressure drop decrease with the increase of the rotational velocity for low rotation of the drill pipe, reaches a minimum value and increases with highest rotations. The increase in torque as a function of rotational speed is more evident at low rotations and the mechanical energy have a linear increase while the drill pipe rotation increase. Investigating the relationship between the cuttings cleaning efficiency and the energy required for the process, it is possible to verify that at high rotational velocities of the drill pipe there is no significant change in cleaning efficiency, while the energy needed for the process increases. Thus, the realization of the cleaning process at high rotations can result in waste of energy if ideal operating parameters are not evaluated.

5. ACKNOWLEDGEMENTS

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