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MULTIPHASE FLOW SIMULATION OF CUTTINGS TRANSPORT ON HORIZONTAL WELLS – THE INFLUENCE OF RATE OF PENETRATION ON THE CLEANING PROCESS PERFORMANCE

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Abstract. *The exploration of oil reservoirs by means of horizontal wells is used in large scale worldwide because it increases the contact area between the wellbore and the reservoir, providing a higher productivity to the extraction process. However, some aspects related to this technique, like for instance the efficiency of cuttings transport through the annulus, need to be better understood in order to avoid the formation of a cuttings bed, due to gravitational effects, which decreases the process efficiency. The present study uses computational fluid dynamics (Ansys CFX 16.0 Software) to evaluate how the rate of penetration (ROP) influences cuttings bed formation and pressure drop along the well, which are critical parameters for the cleaning process. The flow is laminar and the Herschel-Bulkley rheological model characterizes the non-Newtonian behaviour of the fluid. The results show that the increase of the rate of penetration leads to an increase of the cuttings bed, changing the flow pattern and decreasing efficiency. The pressure drop along the well also with the increases of rate penetration, due to the obstruction of the flow by the sediments, what can damage the formation besides requiring more power to perform the process.*

Keywords: *Multiphase flow. Cuttings transport. Drilling hydraulics. Horizontal wells. Rate of penetration.*

1. INTRODUCTION

A key issue in drilling horizontal wells is the cleaning of the annulus space by the drilling fluid that favors the transport of the cuttings extracted by the drilling bit. The gravitational force favors the tendency of sedimentation of the cuttings, causing the formation of a sediment bed in the inferior part of the wellbore.

In addition to lubricating and cooling the bit and also avoid unnecessary torque consumption, the drilling fluid helps to remove the cuttings. It is pumped from the surface into the well through the interior of the drilling column and returns to the surface through the annulus space. The particle cleaning performance is dependent on the rheological characteristics of the fluid and the flow pattern of drilling fluid in the annulus. Some other parameters may also influence annulus cleaning like the drilling column rotation, particle size and wellbore eccentricity, affecting the ability of the drilling fluid to efficiently transport the cuttings to the surface.

Commonly used drilling techniques require maintenance of pressure inside the wellbore between the pore and the fracture pressures. As a result, pressure should be accurately predicted and maintained within a suitable range to avoid kick and loss of circulation.

The obstruction of the annulus may influence the torque required for the rotation of the drill string. Some studies have shown that, up to a certain value, the torque decreases due to the acceleration of the flow caused by the obstruction. The increase of the sediment bed favors the increase of the reverse flow, this fact increases the velocity gradient around the drill pipe, increasing the torque of the column, a phenomenon reported by Furini, Gabriel and Siqueira (2013).

One aspect that greatly influences the occurrence of cuttings sedimentation within the annulus is its granulometry. The increase of particle size makes it difficult to transport the sediment, which in turn tends to increase the fraction of accumulated cuttings, a fact observed by Pan et al. (2018). In addition to the rotation of the drilling column, the authors study the effects of rate of penetration (ROP) on the transport of particles. The results show that with the increase of ROP, the amount of particulate material that enters the interior of the annulus increases, which, in turn, increases the height of the sediment bed formed and the volumetric fraction of stationary particles inside the wellbore. The present study will address how the ROP can influence the cleaning of the annulus space, evaluating the operational aspects that can be modified to improve the drilling process, comparing some parameters used in the experimental study to the ones used by Yu et al. (2007) in order to achieve better results.

1.1 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:

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

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:

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

Where g is the gravitational acceleration, β is the drag coefficient between the phases and τ_l is the stress tensor of liquid. The mass conservation equation for solid phase is expressed as:

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

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

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

Where τ_s is the stress tensor of solid phase and P_s is the solid pressure. The dimensionless axial velocity is defined as:

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

Where D_e and D_i are the external and internal diameters, respectively; Q_i is the inlet flow and w is the axial velocity. In order to plot the results in a normalized basis, the dimensionless position inside the annulus is defined as:

$$S = \frac{y - y_i}{y_e - y_i} \tag{6}$$

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.

2. METODOLOGY

For this study, Ansys CFX® software version 16.0 was used. The drilling fluid, with density ρ_f = 1000 kg/m³, presents a non-Newtonian behaviour, characterized by the Herschel-Bulkley rheological model, with yield stress τ_0 = 17.81 Pa, consistency index K = 0.26 Pa.s^n and behaviour index n = 0.74.

The cuttings from the formation has a spherical shape with 3 mm diameter, density ρ_c = 2661 kg/m³ and restitution coefficient 0.9. These values were defined based on the studies of Pang et al. (2018), Ghasemikafrudi and Hashemabadi (2016) and Akhshik et al. (2015).

The drilling column operation parameters were: inner cylinder rotation of 80 rpm and ROP, which ranged from 6.1 m/h to 12.2 m/h. The rates of penetration studied were taken based on the experimental study of Yu et al. (2007). In order to improve the data range, three additional rates were also analyzed to better identify the influence of the parameter. The flow rate of the mixture at the drilling section was 6.3 kg/s, with Reynolds number for the axial flow equal to 1000 (laminar regime). The exit relative pressure was 0 Pa.

2.1 Multiphase model and solution parameters

Table 1 presents the parameters used for the simulation.

Table 1. Parameters used for the simulation.

				Reference
Phase interaction	Drag model		Gidaspow	(Heydari et al., 2015)
	Lift model		Saffman-mei	
	Restitution coefficient		0.9	(Akhshik et el., 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	-
	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	

Eulerian Granular multiphase model was chosen for the simulations because there are regions containing a dense particulate phase and high particle loading.

The simulations were carried out in two stages. At the first stage the fluid was modelled as single-phase for the development of the velocity profile until the system enters the steady state regime and, in the second stage, the gravel enters the annulus at the drill section with different speeds according to the ROP investigated.

2.2 Geometry and computational mesh

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

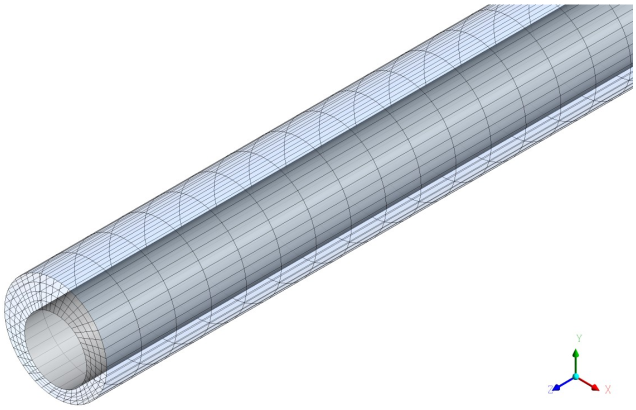

Figure 1. Geometry and mesh used.

3. RESULTS AND DISCUSSION

3.1 Model validation

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

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

Case	Drill Pipe rotation [rpm]	Rate of Penetration [m/h]	Flow rate [m³/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, as 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.

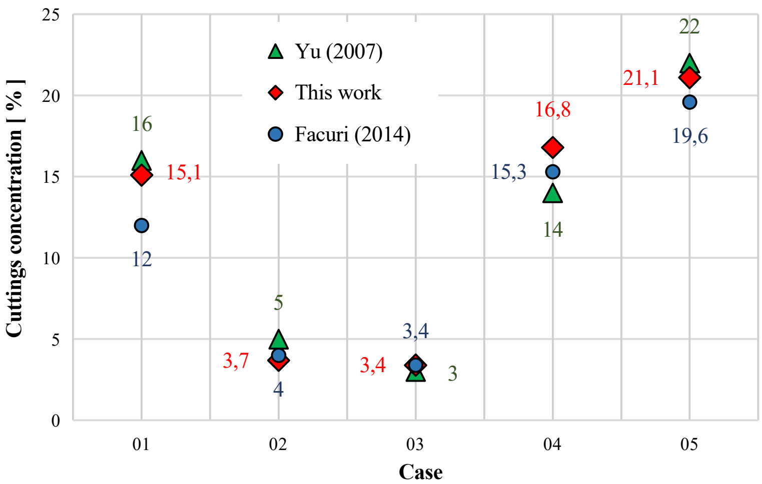

Figure 2. Comparison between the numerical simulations and results available in the literature.

As shown in Fig. 2, the numerical modeling results for the selected cases 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 cleaning process. It is also possible to note that, in the majority of the cases, the results were more accurate than those obtained by 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 Analyze of results

As reported by Osgouei (2010) and Akhshik et al. (2015), the sediments are gradually accumulated and form a bed up to a specific height, where the fluid velocity is high enough to carry the cuttings. Yu et al. (2007) observed the same behaviour using a fluid with different rheological characteristics, but the change in the rheological properties of the fluid lead to a lower cleaning efficiency when compared to the former study. Fig. 1 shows the cuttings concentration values with increasing ROP . The concentration of sediments inside the annulus increases linearly as ROP increases.

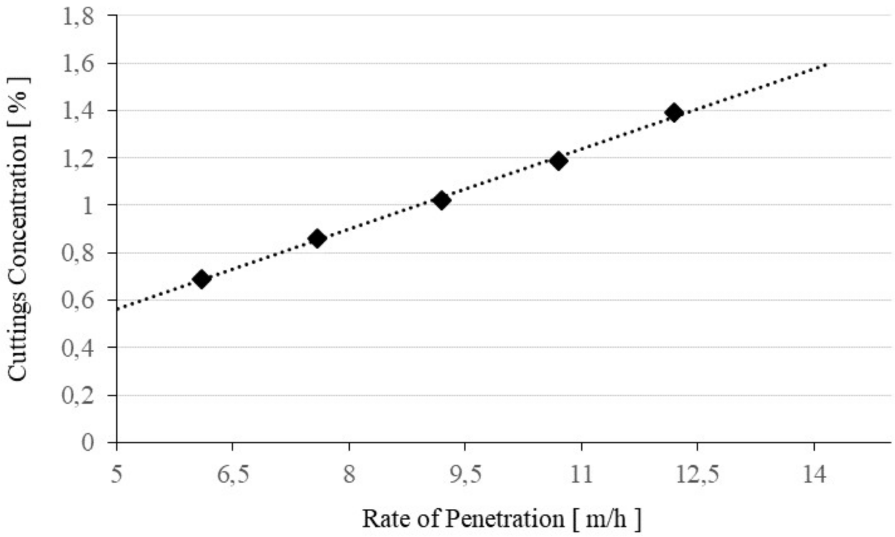

Figure 3 – Effect of rate of penetration (ROP) on cuttings concentration inside the annulus.

As ROP increases, more solid particles are generated and injected into the main flow but its speed is not enough to cause the transport of all the cuttings and the efficiency of the fluid in transporting the sediment decreases. According to Osgouei (2013), ROP is directly related to the total concentration of cuttings inside the annulus. This trend is shown in Fig. 3 and the cuttings concentration distribution is displayed in Fig. 4.

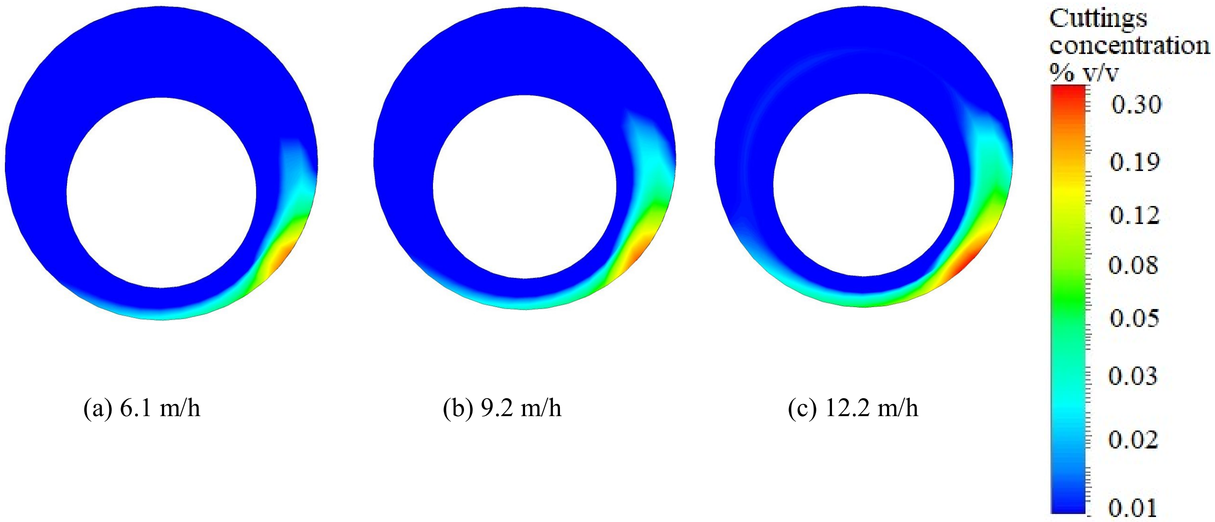

Figure 4 – Cuttings concentration distribution at 12.1 m from the inlet with a drill pipe rotational speed of 80 rpm.

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Furini, Gabriel and Siqueira (2013) reported that larger obstructions of the annulus space favors the occurrence of a reverse flow, modifying the velocity gradient around the drilling column. However, for the case evaluated herein, few changes were observed in the flow pattern, as shown in Fig. 5, because, although a change in the cuttings bed occurred (Fig. 4), the free flow cross-sectional area was almost the same and the majority of the fluid flows through the upper region of the annulus, carrying the cuttings way from the wellbore.

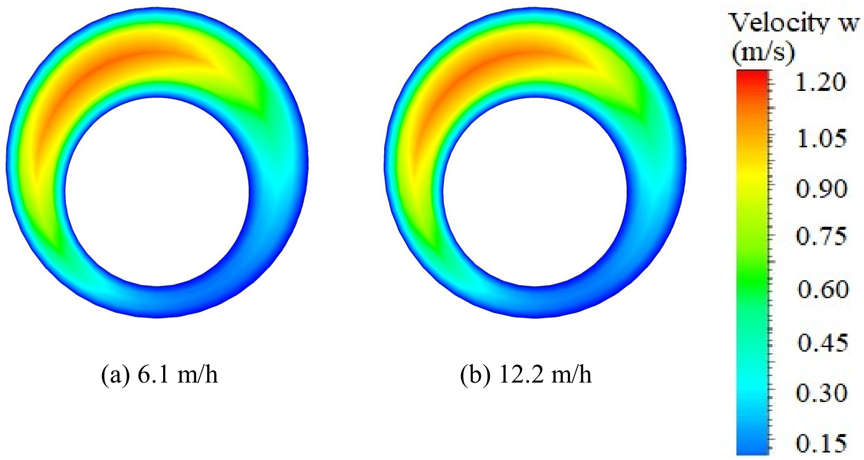

Figure 5 – Velocity contours in a cross-section located at 12.1 m from the inlet with a drill pipe rotational speed of 80 rpm.

The analysis of the velocity profile in the upper gap did not show variation with the change of the rate of penetration (Fig. 6). This phenomenon occurs due to the sediment bed formed in the lower gap, which do not have sufficient height to provide significant changes in the flow pattern, a fact that can also be noticed in the velocity contours of Fig. 5 when analysing the upper gap.

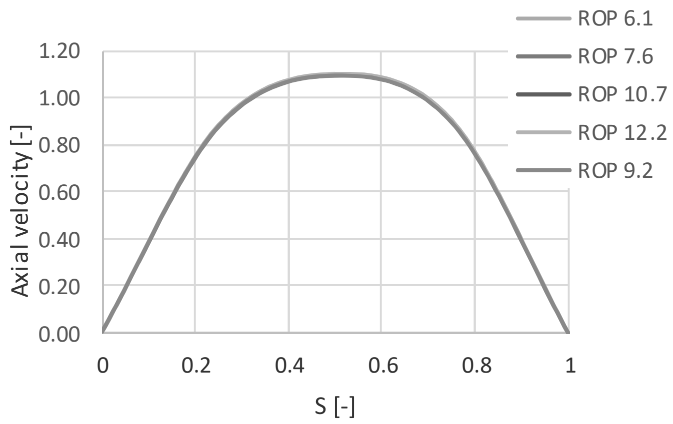

Figure 6 – Axial velocity at the top gap.

Fig. 7 show the axial and tangential velocity profiles at the bottom gap and it can be observed that the increase of ROP changes the velocity profiles. Although quite small, these changes can be explained by the higher gravel concentrations in the lower gap as ROP increases. Using a plate to represent the obstruction in a single-phase flow, Furini, Gabriel and Siqueira (2013) obtained similar results but the results presented herein for the multiphase flow allows a better understanding of the process as a whole.

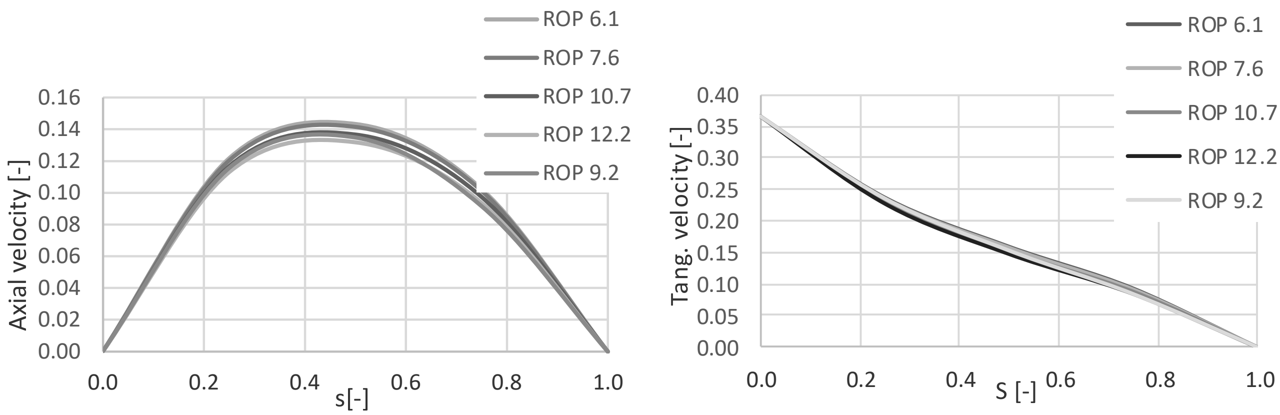

Figure 7 – Axial and tangential velocity bottom gap.

The pressure drop was evaluated for each ROP value, as shown in Fig. 8. Lower pressure drop values were found for the higher ROP. This phenomenon is explained by the fact that as the obstruction of the gap increases with the increase of ROP, the deformation rate also increases in the near wall region and, since the fluid is pseudo-plastic, the increase in the deformation rate leads to smaller apparent viscosities and therefore, smaller pressure drops, which is in agreement with the results found by Khan (2008) and Facuri (2014).

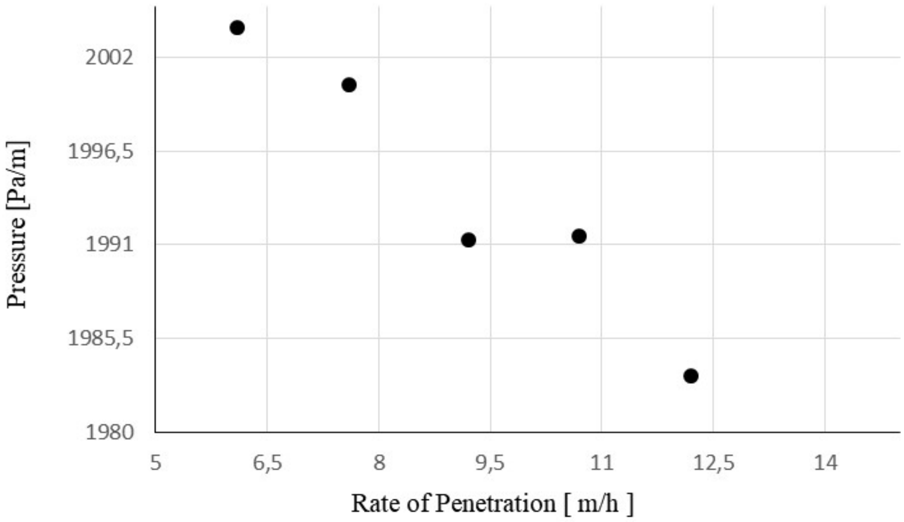

Figure 8 - Pressure drop along the annulus at difrerent rates of penetration.

4. CONCLUSION

The results show that the rate of penetration (ROP) affects the concentration of cuttings accumulated inside the wellbore, due to the larger amount of particulates entering the annulus space. With increased particle concentration in the annulus, the obstruction caused by the cuttings changes the velocity profiles, increasing the pressure drop along the well and a decreasing the cleaning efficiency.

5. ACKNOWLEDGEMENTS

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