

ENC-2020-0306

EXPERIMENTAL EVALUATION OF INTERACTIONS BETWEEN COLUMN/DRILL BIT SET AND CUTTINGS BED IN DRAG FORCE

Mateus Debiasi

Melissa Mayumi Kikuchi

Nezia de Rosso

Cezar Otaviano Ribeiro Negrão

Federal University of Technology-Parana - UTFPR. Rua Deputado Heitor Alencar Furtado, 5000 - Bloco N - Ecoville - CEP 81280-340. Curitiba / PR - Brasil

mateus.debiasi13@gmail.com, melissa.2019@alunos.utfpr.edu.br, nezia.rosso@gmail.com, negrao@utfpr.edu.br

Abstract. During the removal of the column/drill bit set from a horizontal wellbore the drag force is increased. One of the main reasons is due to the interactions between the set and the cuttings bed. The drag increase may even hold the pipe, causing significant cost increase. The objective of the present work is to evaluate the interactions between the column/drill bit set and the cuttings bed during the set removal from a horizontal well. An experimental rig representing the interest situation was built. The rig's testing section represents a horizontal well constituted of a 140 mm internal diameter acrylic pipe. Inside of it, a 76,2 mm diameter aluminum pipe represents the drill column. Both the pipes are 4 m long. The column displacement speed range is within 1 and 10 cm/s. Also, the column may be rotated in a range of 0 to 150 rpm. In order to evaluate the interactions, the varied parameters were: axial displacement speed, rotation, cuttings bed height and the fluid. It was observed that high displacement speed and column rotation reduces the cuttings volume behind the drill bit and the higher viscosity fluid helps the cuttings transportation.

Keywords: Drag force, Cuttings bed, Drill pipe/bit.

1. INTRODUCTION

Vertical wells are a common method for the drilling process. However, sometimes this positioning is not possible due to geographic issues. A possible solution to this matter is the use of directional wells. The drilling deviates from the vertical in an angle that can even reach 90 degrees. In the extreme angle, it becomes a horizontal well. Horizontal wells are also used when the reservoir has a narrow height and the production can be optimized (Petrobras, 2015b). The drilling process occurs due to the drill bit contact with the rock formation. The drill bit cuts the rock into small fragments that are called cuttings (Petrobras, 2015a). In directional wells, the cuttings settle down forming a bed and the sedimentation increases with the deviation angle (Sifferman and Becker, 1997; Wang *et al.*, 2017). Common problems related to this matter are: reduction of rate-of-penetration (ROP), weight-on-bit (WOB) and increase of torque and drag (T&D) loads (Rasi *et al.*, 1994).

The removal of the column from the hole carries cuttings on the cross-sectional area of the bottom hole assembly (BHA) elements and increases the cuttings volume on the drill bit. It happens due to packing velocity of cuttings being greater than the cuttings that are passing through the annular space. There are two known scenarios that may happen during the removal of the column. The first, where a hill is formed on the elements of the BHA and maintains a constant volume. The second case, a plug is formed due to the hill's continuous growth, filling the well's cross-sectional area, which may get the drill string stuck due to excessive T&D (Rasi *et al.*, 1994). Both first and second cases are represented in Figure 1.

In order to avoid such problems as high T&D loads, two approaches to model T&D are commonly used: the soft- and stiff-string. Both methods use a general friction factor, which is not yet well understood and may over or underestimate the T&D values (Mirhaj *et al.*, 2016). However, the friction phenomenon is of great importance on the modeling. The better understanding of the interactions that occurs between the column/drill bit and the cuttings bed may prevent some complications. Aware of this matter an experimental rig to represent a horizontal well was built in a laboratory scale. The objective is to perform tests representing the pulling out of the column with different axial displacement speeds and applying rotation to the column when desirable. Also, different cuttings bed heights made of glass spheres and two fluids with different viscosity are used. The fluids are water and a solution of glucose syrup.

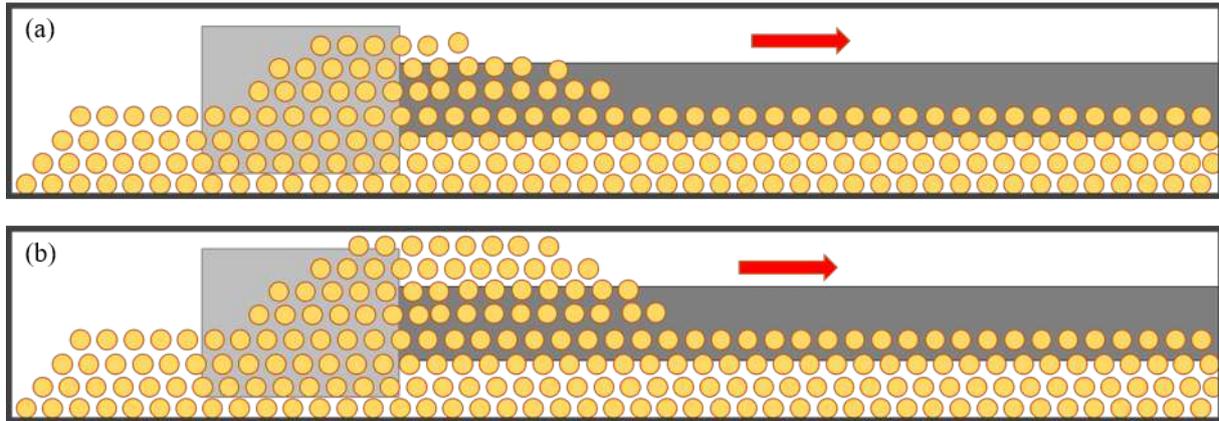


Figure 1. Drill bit removal at the red arrow direction. (a) First case scenario. A hill is formed behind the drill bit without obstructing the cross-sectional area of the well. (b) Second case scenario. The hill continues to grow until the complete well cross-sectional area is filled with cuttings. In this case a plug is formed.

2. LITERATURE REVIEW

Aiming to analyze the complex interactions that occur during the displacement of the column the literature review had four main subjects, which are: torque and drag modeling, experimental evaluation of torque and drag, backreaming and granular media.

2.1 Torque and drag modeling

The first work related to T&D modeling was conducted by Johancsik *et al.* (1984), where they observed that T&D loads are a result of sliding friction. Trying to foresee the T&D loads, the sliding friction was computed by multiplying a friction factor coefficient by the sidewall contact area. The authors stated that for a directional well, seawater-based mud systems, the friction coefficients are in the range of 0.25 to 0.40. Johancsik *et al.* (1984) used a model, where the only cause of T&D was the sliding friction, influenced by the normal force and the friction coefficient.

Mitchell *et al.* (2007) worked on Johancsik's model, using Sheppard *et al.* (1987) equation, and also verified that it fits very well the field data. It is considered a soft-string model, since it neglects the stiffness of the column. The study provided an approximation formula to evaluate the effects of wellbore curvature and torsion. Their T&D model formulation solves the problems related to the wellbore contact considering that the drill string trajectory coincides with the wellbore path. According to the authors, the friction coefficient required to match drag force is significantly different from the one required to match torque. So, to adjust the model they added shear forces, evaluated with a side calculation. This factor is added to the contact force for the torque calculation, due to the rotating drill string tendency to climb the wall. The main error in the T&D model is caused by the assumption of the minimum curvature wellbore trajectory. This method does not consider some contact and axial loads, underestimating the T&D. The work of Aadnoy *et al.* (2010) presented a new friction model that is applied for straight sections, drop-off bends, build-up bends, side bends or a combination of them. It is a soft-string model with the aim of providing a simple tool to model and to study the friction of the well by separating gravitational and tensional friction effects.

It is possible to verify the usage of a general friction factor by analyzing the T&D modeling works conducted over the years. The information about the friction factor and its influence on T&D loads is not well detailed, even though some authors had reported its importance in modeling.

2.2 Experimental works

Only one experimental work in similar conditions to the present work was found in the literature. The author evaluated the effects of variables such as displacement and rotational speed, drill bit open area, and cuttings bed height on T&D. Rasi *et al.* (1994) states that for horizontal wells the elements of the BHA tend to plow the cuttings bed during the axial displacement. So, a critical height was determined to characterize the tendency of plug formation. He determined through a series of laboratory experiments some critical heights for the cuttings bed. If the region above the cuttings bed is higher than the critical height, no problems during the axial displacement of the column were found, on the contrary, the pipe may get stuck. He also used several models of BHA that were pulled inside transparent pipes partially filled with cuttings bed. He varied the pipe size, bit cross-sectional area and shape, collar length and outside diameter, initial cuttings bed height, type of cuttings and wellbore inclination. With these experiments, two main conditions were observed. Firstly, the pipe displacement creates a hill of cuttings that grows in the beginning of the movement and soon stops growing,

maintaining a continuous length without increasing the overpull. This condition was found when the cross-sectional area of the largest element of the BHA was smaller than the open area above the cuttings bed. Secondly, the hill increases continuously with the pipe motion rising the overpull and sometimes exceeding pulling capabilities. In this case, the BHA elements are larger than the open area above the cuttings bed.

2.3 Backreaming

Backreaming is a technique to pump fluid and rotate the drill string during the pulling out of the hole. It is used when there is a problem to pull the column out without rotation, to eliminate tight-hole conditions and to clean the hole to eliminate cuttings beds and hole cavings. The backreaming can be used in conditions where the axial displacement cannot be done without the risk of stuck pipe. According to Yarim *et al.* (2010), backreaming may cause the problems that it should avoid, if performed where there is a significant amount of cuttings. Therefore, it is a technique that is used only as a last resort. Although the backreaming technique can contribute to reduce friction, it may cause serious problems to the drill string due to vibration (Agostini and Nicoletti, 2014). The excitation can result in a displacement of lateral, axial, torsional or a combination of all of them. If the vibration is tuned to the natural frequency the result can be fatigue or failure of the drill string. During this process the critical speeds are higher when compared to normal conditions, that is why cautions must be taken (Samuel and Mirani, 2015).

2.4 Granular media

Trying to understand the complex phenomena that occurs during the displacement of the column/drill bit on a cuttings bed, a literature review about granular media was conducted, even if not in the same conditions found in the current work. Considering the ratio of shear forces and grain weight, the grains may be carried as a granular layer that can slide, roll or even perform small jumps. An experiment to visualize this movement, called bed loads, was performed by Penteado and Franklin (2015). The water flow conditions were used to correlate with the measured data of the bed loads displacement, then compared with the semi-empirical expressions from literature. The author concluded that the results fit the literature expressions.

Nazari *et al.* (2010) found that the models of cuttings concentration usually do not consider all the field conditions because of the simplifications. This imposes some limitations to the model, since they have limited parameters monitored. A full-scale wellbore simulator at low pressure and temperature was used. With the simulator they observed that increasing the hole angle increases the hydraulic need for hole cleaning. The authors observed that the transport of smaller cuttings is more difficult and that annular cuttings concentration and bed height are two hole cleaning parameters that need to be monitored. Zhou (2008) also observed that the smaller the cuttings the higher the flow velocity needed to transport them. The decrease in the velocity decreases the cuttings transport capability. Based on the results, he stated that the cuttings volume at the annulus is sensitive to the liquid flow rate.

Allen and Kudrolli (2018) developed an apparatus of a cylindrical container, with a conical top plate that could be rotated with a previous set frequency. This rotation would apply to the fluid a uniform shear stress, so it would be possible to understand the behavior of a bed of monodisperse spherical grains to the fluid flow. The test start point was a freshly sedimented bed, that compacts with the granular volume fraction growth. When vibration is applied, the packings compact rapidly and grow logarithmically. This growth is associated with the jamming transition for spheres, where a large number of grains rearranged, creating space for more grains. The deep shear-induced relation of the bed causes the bed armoring. That is the reason for the volume fraction increase. The authors demonstrate that to erode the bed, a significantly higher shear stress is needed after the application of a sub-critical shear. Thus, there is a systematic increase in the erosion.

An experimental study on ripples formation and migration was performed by Florez and Franklin (2015). A turbulent channel flow was used with different water flow rates. During the experiment the authors observed a reduction of the celerity from the beginning to the end of the test. Also, Franklin and Ayek (2013) performed an experiment of perturbation on a two-dimensional hill with a fully-developed turbulent boundary condition. The experimental apparatus was a five-meters long rectangular cross-section channel fed with water by a progressive pump with a flow straightener, a settling tank and return line. Three regions were observed by the authors: a small perturbation far from the ripple surface, a recirculation bubble area on the ripple's surface and a stronger perturbation down and upstream of the crest, where the maximum shear stress occurs. The flow shear stress is stronger on the ripple's surface and decreases as the distance from the surface grows.

Wiktorski *et al.* (2018) have studied frictional forces, eccentricity, torque and rotation. Using a flow rate that the local liquid velocity is above the critical flow velocity, resulted in separate particle dunes. By increasing the flow, a homogeneous suspension of particles is created. According to the author, the friction factor in horizontal well can be a function of flow rate and rotation if the eccentricity is also assumed as a function of them. Besides, the bed height is function of flow rate. A laboratory experimental work was performed by Cúñez and Franklin (2019) where the liquid-solid fluidized beds were studied in a narrow vertical tube. A water reservoir, heat exchanger, centrifugal pump, flow meter, flow homogenizer, one-inch tube and a return line was the setup used for the experiment. The authors observed granular

plugs and voids occupying the hole tube, and these plugs depended strongly on the water flow, not on the initial height.

3. METHODOLOGY

The experimental rig was developed to reproduce the pulling out of the hole maneuver in a horizontal wellbore, see Figure 2. The project was done in order to control the axial displacement speed, apply rotation when suitable and form the cuttings bed with different heights. The column movement is controlled by a computer, using two softwares: LabVIEW that enables the power of the motor and servo, and controls the rotation of the column, and Lightening, a software by Hiwin, which controls the column displacement. The experimental rig is composed of three main systems: the testing section, which represents the horizontal well; the mechanical system, responsible for performing the column movements; and the data acquisition system, that register the readings from the load cells and video recording.

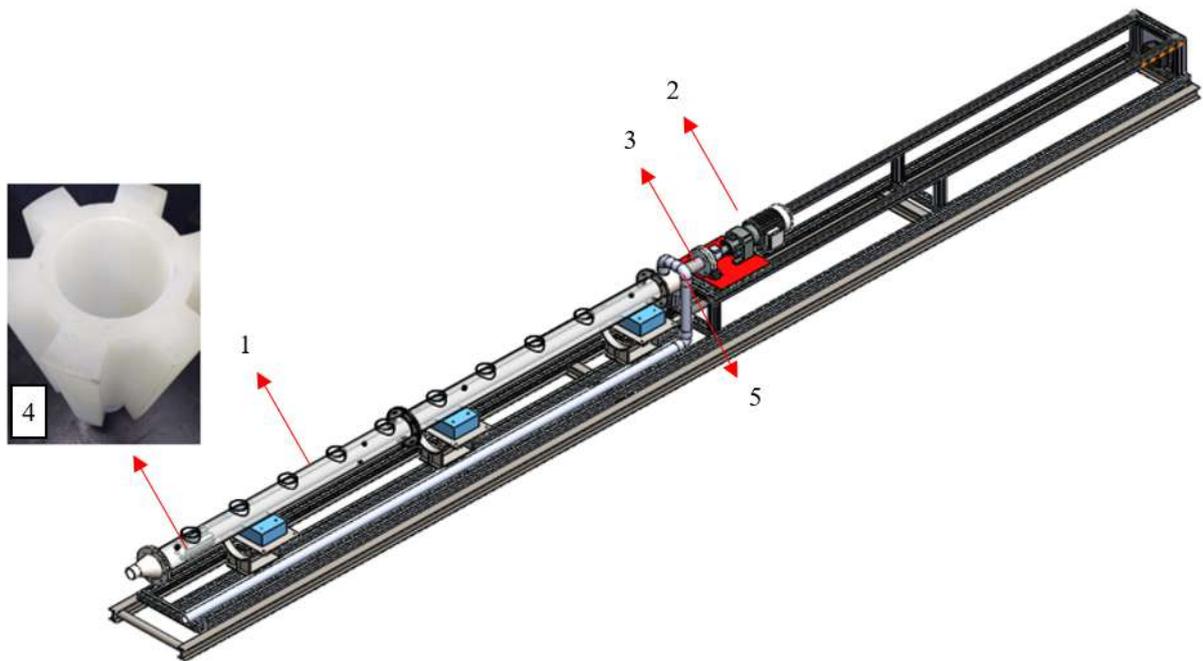


Figure 2. Experimental rig. (1) Acrylic pipe that represents the well. (2) Mechanical subsystem that is responsible for the axial displacement and rotation. (3) Aluminum pipe that represents the drill column. (4) Polypropylene drill bit model, inside the acrylic pipe. (5) Fluid entrance at well top.

The test section is shown in Figure 3. The wellbore is represented by a four-meters acrylic pipe with 140 mm of internal diameter. The acrylic pipe is composed of two pipes of two-meters each, attached by flanges. On the upper side of the pipe, a total of nine four-inches openings were built to make possible the cuttings bed arrangement. The column is represented by a four-meters aluminum pipe, with 76.2 mm of external diameter.

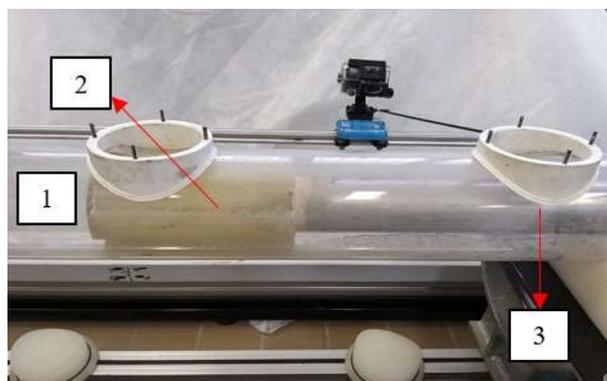


Figure 3. Test section. (1) drill bit. (2) acrylic pipe which represents the wellbore. (3) aluminum pipe which represents the drillstring.

The components of the mechanical system are shown in Figure 4. A four-meters ball screw with 50 mm diameter is driven by a servomotor. This servomotor, an Hiwin model FRMS752B608C, with nominal rotation of 3000 rpm and a 9.2

Transtecno reduction type CMB502, is placed at one end of the ball screw. It is powered and controlled by the software Lightning. The ball screw rotation is responsible for transporting the nut at 10 mm pitch which is attached to a traction load cell sensor. The plate is guided by linear guideways. This system is responsible for the column displacement, which has a three-meters path with emergency stop-buttons. There is a motor on the plate, model SK80S/4, responsible for the column rotation.

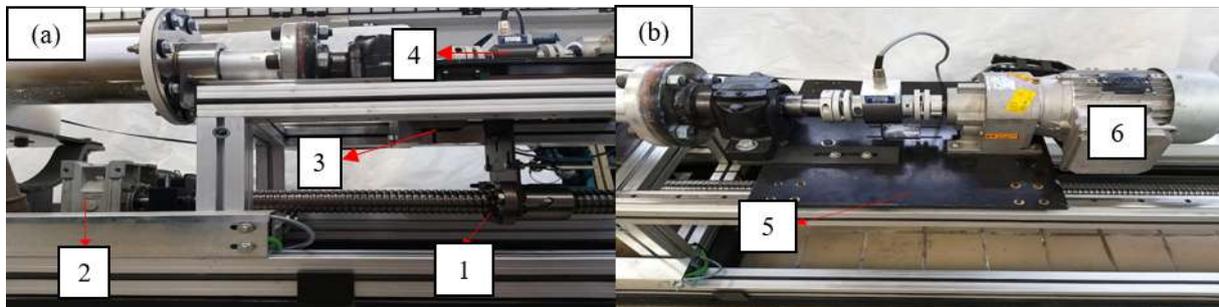


Figure 4. Mechanical and data acquisition systems. In figure (a) the axial displacement subsystem. (1) Ball screw. (2) Servomotor. (3) Traction load cell model S9N.(4) Torque load cell model T22. Rotation subsystem in figure (b). (5) The plate that moves the motor while the axial displacement of the column.(6) Motor responsible for the rotation.

The data acquisition system is composed of a National chassis NI cDAQ-9188 with three slots used for the acquisition, a traction and a rotation load cells (shown in Figure 4), and pressure transducers. The system communicates via LabVIEW. The traction load cell, an HBM S9M of 2000 N of nominal force, is placed under the plate where the column is located. It reads the forces that are required to displace the column during its axial movement. It operates in a frequency of 2000 Hz at continuous reading of 4000 samples with an accuracy class of 0.02. The rotation load cell, an HBM T22 of nominal torque of 50 Nm, is fixed on the plate, attached between the column and the motor that is responsible for the column rotation. The torque is also read at the frequency of 2000 Hz and 4000 samples with an accuracy class of 0.5. Both load cells are installed with cable filters and the wires are placed in different sides of the rig to avoid electric noise. A wire transformer was also installed to avoid electric noise.

3.1 Test procedure

Regarding to the column displacement of a horizontal well with cuttings bed tests, some variables were defined. The tests are performed by fixing five variables and changing the sixth. In order to represent the cuttings, glass spheres of three-millimeter diameter and 2600 kg/m were used. Two fluids were used to verify the influence of fluid viscosity. The fluids are water and a solution of glucose syrup, at 1 cP and 65 cP, respectively.

The test procedure begins by creating a cuttings bed. The cuttings bed height is defined and a level is used in order to create a constant height bed with the glass spheres. The possible heights are 33, 50 and 70 mm, which correspond respectively to 25, 35 and 50% of the total height. The second step is to fill the well with the working fluid, water or the glucose syrup solution. Once the wellbore is filled with the working fluid, the bubbles are removed and the column is placed in the point zero of the test. At this location, the column is able to move in a path of three meters.

The test setup is ready and the test parameters are inputted in the computer. The column moves at the axial displacement speed that was defined, being able to rotate if desirable. When the column reaches the end of the three meters path, a hill or a plug of cuttings will be formed and the data acquisition systems will have recorded the drag force. The path may not be complete if the drag exceeds the apparatus limit force, which will characterize the stuck pipe situation

4. RESULTS

Tests with different displacement and rotational speeds and cuttings bed heights were performed. The Figure 5 show the force level during the removal of the column on the vertical axis and the time on the horizontal one. The displacement speed is 1 cm/s, using water as the working fluid, on a 70 mm (50%) cuttings bed height. One case without rotation and the other with.

Initially, it is observed a drag force increment when the drill bit hits the cuttings bed. As the set continues the displacement at 1 cm/s, the cuttings volume behind the drill bit continues to grow. This situation resulted in a plug due to the combination of a great amount of cuttings (50% of the height) and the slow displacement speed. The plug is shown in Figure 6. With the continue cuttings volume growth the force shows an exponential growth what was also observed by Rasi *et al.* (1994), seen in the red line with triangles. The experiment was interrupted when the force reached the apparatus limit.

However, the plug formation and the stuck pipe may be avoided when the column is rotated. The drag force result for

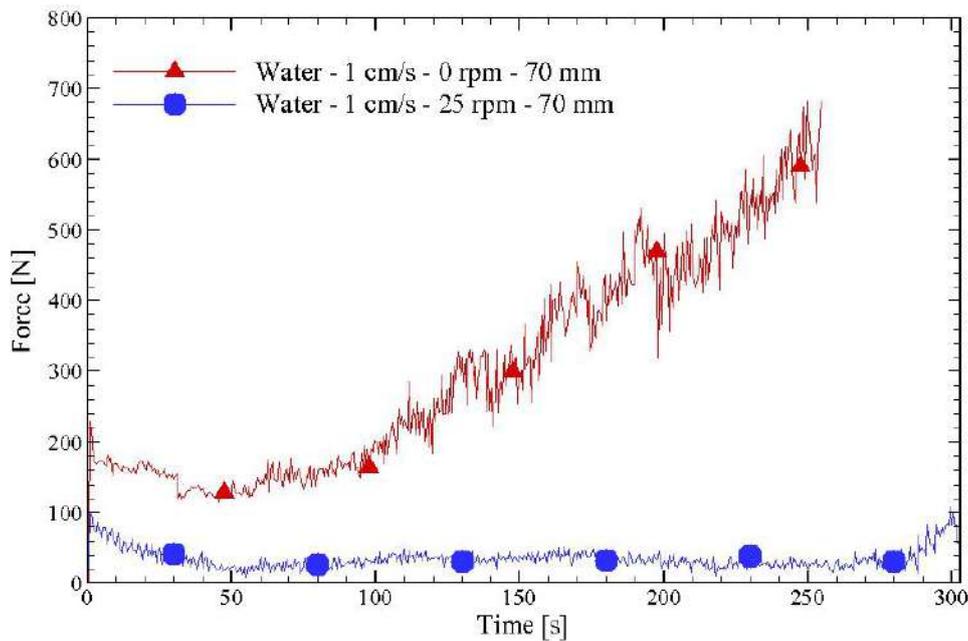


Figure 5. Test comparison of 1 cm/s displacement speed on a 70 mm cuttings bed height using water with and without rotation. The red line with triangles shows the test without rotation and the blue line with circles the test with rotation.

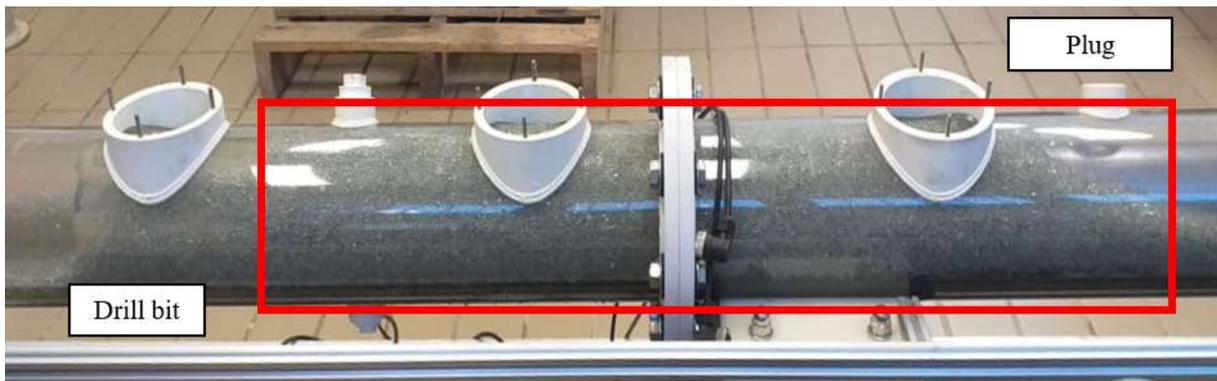


Figure 6. Plug formation behind the drill bit after a test at 1 cm/s displacement speed, no rotation on a high cuttings bed and water as the working fluid.

the rotating case is shown in the blue line with circles in Figure 5. The force level remains almost constant during the whole test. The plug formation is avoided due to the fluid flow through the annular space that drags the cuttings that were lifted by the rotating bit, see Figure 7.

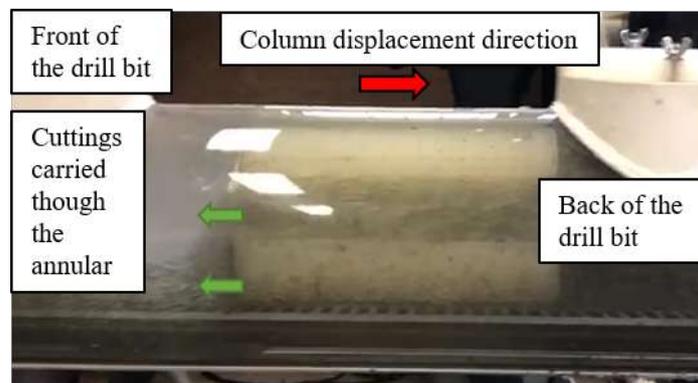


Figure 7. The influence of rotation on the displacement of the drill bit and cuttings movement.

The drill bit shape creates a situation where the rotation breaks the cuttings bed by moving the cuttings from the bottom of the hole to the top. This movement and the displacement of the column result the increase of the cuttings transport to

the front of the drill bit. Even though the conditions are the same besides the rotation, the plug formation was avoided in this case. The result was a hill of cuttings, shown in Figure 8. Also, the pipe does not get stuck for 25 and 35% cuttings bed heights due to the small cuttings volume behind the drill bit.

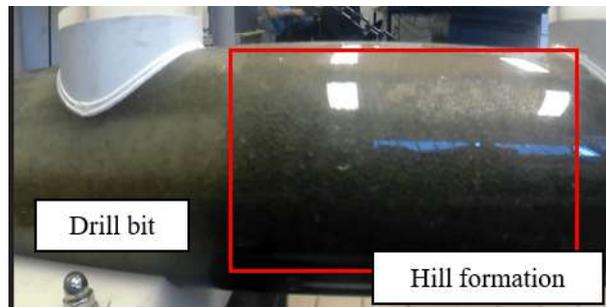


Figure 8. Hill formation behind the drill bit.

The same comparison was done to the glucose syrup solution. Using a solution of glucose syrup at 65 cP as the working fluid, some different results were found. The comparison of the rotating case and the non rotating one is shown in Figure 9.

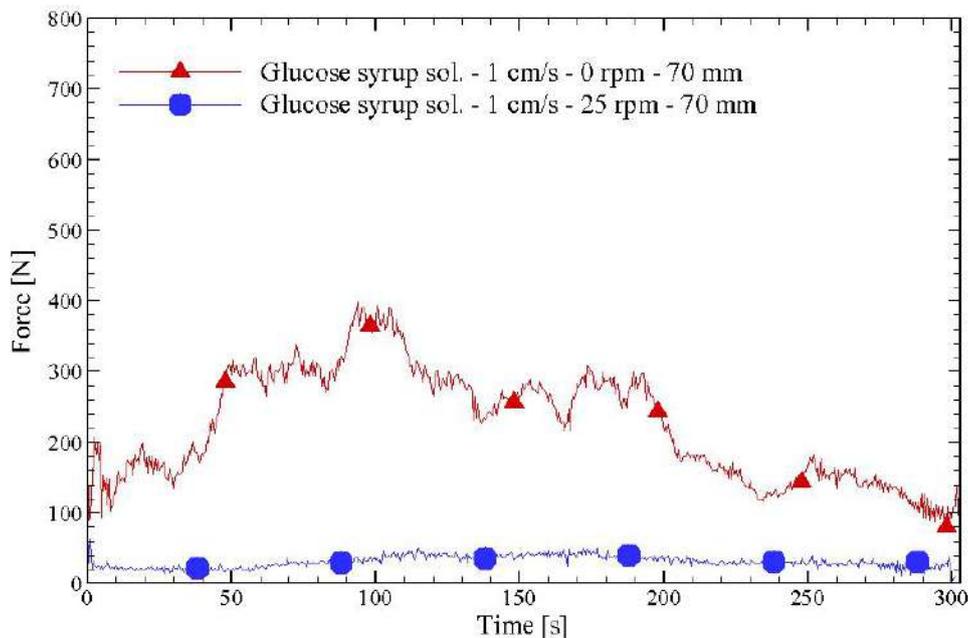


Figure 9. Tests comparison of 1 cm/s displacement speed on a 70 mm cuttings bed height using a solution of glucose syrup with and without rotation. The red line with triangles represents the test without rotation and the blue line with circles the test with rotation.

The plug formation was not experienced for the same condition as the water tests. The drill bit presents some edges where there is space between each one. It is possible to see in the red line with triangles in Figure 9 the moments that the cuttings pass through the gaps on the drill bit. What is not possible using water as the working fluid. The glucose solution increases the amount of cuttings that is carried to the front part of the drill bit. Since during the hill's growth, the cuttings face the edges of the drill bit, the drag force increases until the cuttings reach the gap between edges, which helps the fluid to carry the cuttings. Since the cuttings volume on the back of the drill bit diminishes, the plug formation does not happen. Besides, the column rotating case, blue line with circles in Figure 9, show similar results for the glucose solution when compared to water.

Another result that avoided the plug formation was for high displacement speeds. Two tests of 10 cm/s displacement speed on 70 mm cuttings bed height are shown in Figure 10.

The column high displacement speed increases the fluid flow and the cuttings transport to the front of the drill bit. The last comparison is of water and glucose syrup solution at 10 cm/s at a high cuttings bed. The amount of cuttings behind the drill bit gets lower and the drillstring does not get stuck in the wellbore. The results for the high displacement speed test with water is shown in the red line with triangles and the glucose syrup solution in the blue line with diamonds in Figure 10.

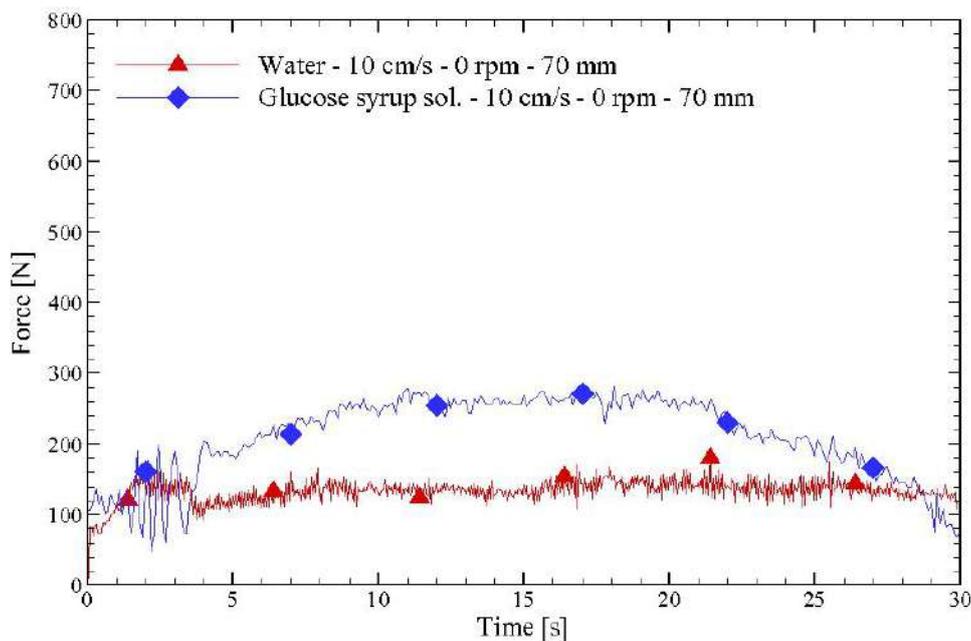


Figure 10. Tests comparison of 10 cm/s displacement speed without rotation on a 70 mm cuttings bed height with water and the glucose syrup solution. The red line with triangles represent the test with water and the blue line with diamonds the test with the glucose syrup solution.

It is observed that the drag force required to remove the column using the higher viscosity fluid is greater than the force required to move the column in water. Since the fluid must fill the volume that was occupied by the drill bit and column as it moves out of the test section, the higher viscosity of the glucose increases the drag force since it flows with more resistance than the water. Even with this difference, the result is similar for both working fluids.

5. CONCLUSIONS

It was observed a plug formation for high cuttings bed and low displacement speed without column rotation. The plug resulted in a stuck pipe with the drag force growing exponentially. The stuck pipe situations for high cuttings bed and low displacement speed were avoided by rotating the drill pipe. It was observed that the rotation of the drill bit moves the cuttings from the bottom to the top of the cross-sectional area of the well. This movement breaks the structure of the cuttings bed and corroborates to the displacement of the cuttings to the front of the drill bit. Also, by increasing the displacement speed made easier the movement of the cuttings from the back to the front of the drill bit diminishing the drag force. For low cuttings bed height, the pipe never got stuck For the tests using glucose syrup solution, the rotation and high displacement speed cases showed similar results when compared to water. However, the plug situation was not experienced. The fluid was able to carry the cuttings through the drill bit gaps, which resulted in less drag force and less cuttings behind the drill bit.

6. REFERENCES

- Aadnoy, B.S., Fazelizadeh, M. and Hareland, G., 2010. "A 3D analytical model for wellbore friction". *Journal of Canadian Petroleum Technology*, Vol. 49, No. 10, pp. 25–36. ISSN 00219487. doi:10.2118/141515-PA.
- Agostini, C.E. and Nicoletti, R., 2014. "Lateral vibration of oilwell drillstring during backreaming operation". *Proceedings of the International Conference on Structural Dynamic , EURODYN*, Vol. 2014-Janua, No. July, pp. 893–898. ISSN 23119020.
- Allen, B. and Kudrolli, A., 2018. "Granular bed consolidation, creep and armoring under subcritical fluid flow". Vol. 01610, pp. 1–21. URL <http://arxiv.org/abs/1805.00838>.
- Cúñez, F. and Franklin, E.d.M., 2019. "Experimental Investigation of Liquid-Solid Fluidized Beds in a Narrow Tube". doi:10.26678/abcencit2018.cit18-0087.
- Florez, J.E.C. and Franklin, E.d.M., 2015. "Experiments on the instabilities of a granular bed in a turbulent flow". *IV Journeys in Multiphase Flows*, Vol. 6, No. 1. ISSN 10706631. doi:10.1063/1.868074.
- Franklin, E.d.M. and Ayek, G.A., 2013. "Experimental Measurements of a Turbulent Flow Over a low hill". *22nd Internation Congress of Mechanical Engineering*, , No. Cobem, pp. 309–318.
- Johancsik, C.A., Friesen, D.B. and Dawson, R., 1984. "Torque and Drag in Directional Wells - Prediction and Measure-

- ment.” *JPT, Journal of Petroleum Technology*, Vol. 36, No. 7, pp. 987–992. ISSN 01492136.
- Mirhaj, S.A., Kaarstad, E. and Aadnoy, B.S., 2016. “Torque and drag modeling; Soft-string versus stiff-string models”. *Proceedings of the SPE/IADC Middle East Drilling Technology Conference and Exhibition*, Vol. 2016-Janua, No. January, pp. 26–28.
- Mitchell, R.F., Samuel, R. and De, H., 2007. “How Good is the Torque-Drag Model?” *SPE/IADC Drilling conference*.
- Nazari, T., Hareland, G. and Azar, J., 2010. “Review of Cuttings Transport in Directional Well Drilling: Systematic Approach”. *Proceedings of SPE Western Regional Meeting*. doi:10.2523/132372-MS. URL <http://www.spe.org/elibrary/servlet/spepreview?id=SPE-132372-MS>.
- Penteado, M.R.M. and Franklin, E.D.M., 2015. “An Eulerian Approach for Bed Load Determination Using a High-Speed Camera”. *IV Journeys in Multiphase Flows*, p. 7.
- Petrobras, 2015a. “A descoberta de um campo de petróleo e gás natural em 5 passos”. URL <http://www.petrobras.com.br/fatos-e-dados/a-descoberta-de-um-campo-de-petroleo-e-gas-natural-em-5-passos.htm>.
- Petrobras, 2015b. “Conheça os diferentes tipos de poços de petróleo e gás natural”. URL <http://www.petrobras.com.br/fatos-e-dados/conheca-os-diferentes-tipos-de-pocos-de-petroleo-e-gas-natural.htm>.
- Rasi, M. *et al.*, 1994. “Hole cleaning in large, high-angle wellbores”. In *SPE/IADC Drilling Conference*. Society of Petroleum Engineers.
- Samuel, R. and Mirani, A., 2015. “Vibration modeling and analysis under backreaming condition”. *Proceedings - SPE Annual Technical Conference and Exhibition*, Vol. 2015-Janua, No. September, pp. 1034–1049.
- Sheppard, M.C., Wick, C. and Burgess, T., 1987. “Designing Well Paths To Reduce Drag and Torque.” *SPE Drilling Engineering*, Vol. 2, No. 4, pp. 344–350. ISSN 08859744. doi:10.2118/15463-PA.
- Sifferman, T.R. and Becker, T.E., 1997. “Hole cleaning in full-scale inclined wellbores”. *SPE Reprint Series*, , No. 44, pp. 16–21. ISSN 08910901.
- Wang, X., Chen, P., Ma, T. and Liu, Y., 2017. “Modeling and experimental investigations on the drag reduction performance of an axial oscillation tool”. *Journal of Natural Gas Science and Engineering*, Vol. 39, pp. 118–132. ISSN 18755100. doi:10.1016/j.jngse.2017.01.018. URL <http://dx.doi.org/10.1016/j.jngse.2017.01.018>.
- Wiktorski, E., Khatibi, M., Sui, D. and Time, R.W., 2018. “Study of Frictional Forces Between Rotating Pipe and Wellbore in Horizontal Wells: Experimental and Modeling”. p. 10. doi:10.1115/omae2018-77105.
- Yarim, G., Ritchie, G.M. and May, R.B., 2010. “A guide to successful backreaming: Real-time case histories”. *SPE Drilling and Completion*, Vol. 25, No. 1, pp. 27–38. ISSN 10646671. doi:10.2118/116555-PA.
- Zhou, L., 2008. “Hole Cleaning During Underbalanced Drilling in Horizontal and Inclined Wellbore”. *SPE Drilling & Completion*, Vol. 23, No. 03, pp. 267–273. ISSN 1064-6671. doi:10.2118/98926-pa.

7. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.