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SEDIMENT PARTICLE ENTRAINMENT IN AN OBSTRUCTED ANNULAR

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Abstract. *Flow in an annular region with internal cylinder rotation is a classic problem in fluid mechanics and has been widely studied. Besides its importance as a fundamental problem, flow in annular regions has several practical applications. This project was motivated by an application of this kind of flow to the drilling of oil and gas wells. In this work, an erosion apparatus was constructed in order to study the effect of the internal cylinder rotation on particle entrainment in an obstructed annular space and bed package as well. The study also analyzed the influence of height of the particles bed on the process performance. The experiment was designed so that the internal cylinder rotation could be measured by an encoder. The fluid temperature was measured by a thermocouple and the experiments were carried out at the temperature of 25ºC. The study revealed that the particle entrainment for the height of the bed that is close to the center of the cylinders is negligible and the internal cylinder rotation provokes the movement and packing of the bed. For lower height of the bed, with same dimension of the annular gap, the particle entrainment process was satisfactory and the bed compactation was smaller than in the previous case, leading to a more efficient cleaning process in the annular space.*

Key words: Sediment particle, entrainment, obstructed annular.

1. Introduction

The technological advance during the last decades has contributed to the enhancement of drilling process. However, the inadequate cleaning of the wells can lead to several drilling problems like, increase in the torque of the drill pipe, mechanical pipe sticking and difficulties on casing/cementing and logging operations, causing a significant increase in the well cost (Azar and Sanchez, 1997).

Among the main parameters that can affect the hole cleaning, one can quote: the velocity of the fluid in the annular space; the flow regime; eccentricity and drillstring rotation; rate of penetration; well inclination angle; rheological properties of the drilling fluid; and size, shape and density of the sediment particles. From these parameters, the axial velocity of the fluid in the annular space is considered the most important but the other parameters play an important role on the cleaning process either by its own relevance to the process or by changing the main flow pattern.

Zamora and Jefferson (1995) have studied the hole cleaning and suspension in horizontal wells and stress the importance of well profile and annular geometry on the cleaning process. As pointed out by the authors, annular geometry variations affect annular velocity and shear rate, influencing the hole cleaning performance. Drillstring eccentricity also affects the velocity profile and can influence sediment particles bed formation. This fact forces the majority of fluid flow along the upper side of the wellbore (above the pipe), away from sediments that tends to settle on the low side, hindering an efficient transport.

As described above, the axial flow velocity is the main responsible for entrainment and transport of sediment particles. However, drillstring rotation can also contribute to the entrainment of particles into the fluid, which will be carried away by the axial flow. The understanding of the effects of drillstring rotation on flow pattern, like for instance the creation of Taylor vortices (Philip *et al.*, 1998), and sediment particles bed formation can contribute to the improvement of drilling process.

Following the works of Silva and Martins (2002) and Loureiro (2004), this work investigates the influence of the drillstring rotation on the development of the bed form and particles entrainment, which can assist the cuttings transport by the axial annular flow.

2. Experimental facility

The experimental facility, i.e. the annular flow erosion simulator, is shown in Fig. 1. It consists of a 2.0 m long annular tube with the outer diameter of the inner cylinder equal to 165 mm and the inner diameter of the outer cylinder equal to 314 mm. The lids on the top were used to introduce the sediment particles and water into the simulator and also to adjust the sediment particles bed level so that it become horizontal following the inclination angle that was set to zero. A motor connected to the inner cylinder by a system of belts and pulleys creates the momentum necessary to rotate the drillstring. An encoder attached to the inner cylinder measured its angular velocity, which could be controlled by changing the motor rotational speed. The fluid temperature was measured by a thermocouple and the experiments were carried out at the temperature of 25ºC. The sediment particles bed profile was measured using an ultra-sound sensor which emits a signal that is reflected when it reaches the sediment particles bed. The reflected signal is captured by the sensor and the distance between the sensor and the bed is calculated using a calibration curve previously obtained. The ultra-sound sensor window used to measure the sediment particles profile was placed at the center of the section of the simulator so that the effects of the extremities of the tube did not interfere on the bed profile. In fact, extremity effects were only noticed very close to the extremities of the tube (no more than 0.2m from the extremity wall).

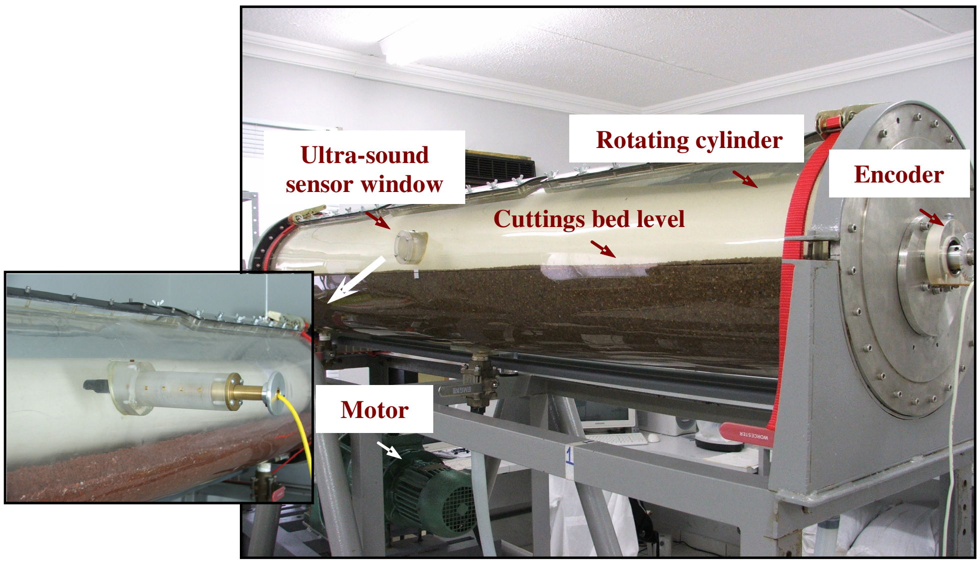


Figure 1. The annular flow erosion simulator.

3. Experimental procedure

At this stage, the size, shape and density of the sediment particles were kept constant. The mean diameter of the particles was d50 = 3.2 ± 0.8mm, the circularity equal to 0.88 ± 0.19 and a specific weight of 24.4 kN/m^3.

The initial packing of the sediment particles bed (ratio between the sediment weight and the volume that it occupies into the annular space), was 16.1 kN/m^3. When compared to the specific weight of the sediment particles, it indicates that around 33% of the sediment bed is not filled with particles.

Three different cuttings bed levels were tested: H/R = 0.47; H/R = 0.74 and H/R = 1.0, where H is the bed level and R is the inner radius of the outer cylinder. H/R = 0 corresponds to no cuttings bed at all, while H/R = 1.0 represents half of the volume in the annular space filled with cuttings. The value H/R = 0.47 means that the cuttings bed level is tangent to the inner cylinder and H/R = 0.74 is an intermediate level.

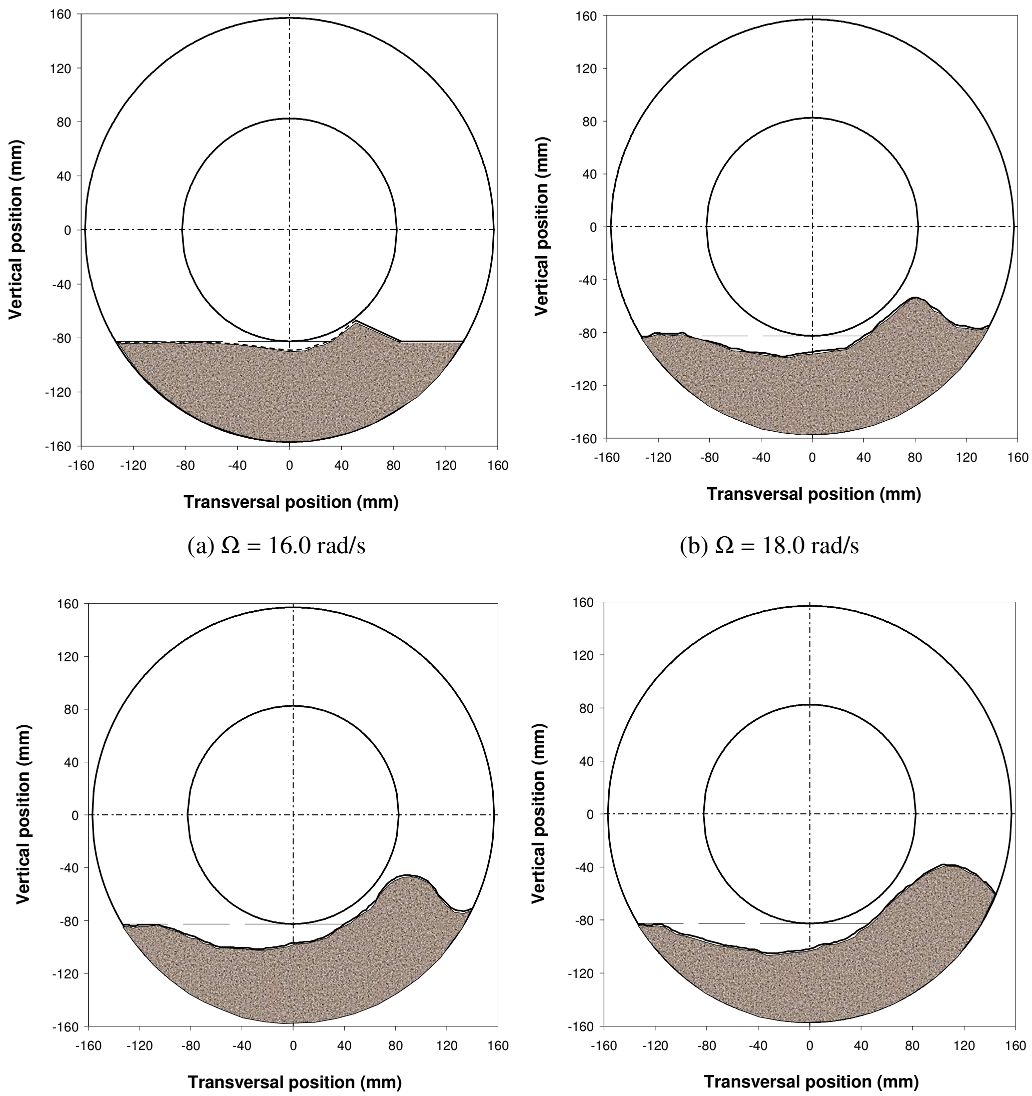
The angular velocity of the inner cylinder was controlled by an encoder connected to the cylinder. Ten different velocities were tested varying from 4.0rad/s to 22.0rad/s. For each velocity the experiment was left to run for one hour after which the experiment was stopped and the sediment particles bed level was measured. The bed form obtained at one velocity was used as start condition for the next velocity.

For the experiments where the fluid could freely flow through the annular gap formed between the sediment bed and the inner cylinder the bed profile was measured using an epoxy filament that was placed over the sediment particles bed and let dry for 24 hours assuming the form of the bed profile. This profile was then passed to a paper and digitalized afterward. The second technique used to measure the bed profile was the ultra-sound sensor as previously explained. However, under the inner cylinder, measurements were not possible with the ultra-sound system and since for this region the bed form varied linearly with the distance from the cylinder, the angular distance from the center line to the point where the sediments starts touching the cylinder was measured and a straight line was drawn connecting this point to the best fit line obtained for the measurements with the ultra-sound system. There were still some cases where it was not possible at all to measure the bed profile under the cylinder. In this case, the bed profile was visually estimated and the sediment particles bed profile is only qualitative and represented by a dashed line in the figures.

4. Results and discussion

The influence of drillstring rotation on cuttings bed profile was evaluated for three different bed levels. Figure 2 shows the results obtained for H/R = 0.47 (bed level tangent to the inner cylinder).

For angular velocities up to 14rad/s the bed form did not change considerably and therefore these results are not presented here. According to Fig. 2a, for the velocity of 16rad/s, the sediment particles bed profile starts to change its shape and the sediments initially placed below the cylinder were carried to the right, increasing the gap below the cylinder and forming a small heap of sediments adjacent to it.



(a) Ω = 16.0 rad/s

(b) Ω = 18.0 rad/s

(c) Ω = 20.0 rad/s

(b) Ω = 22.0 rad/s

Figure 2. Influence of drillstring rotation on sediment particles bed evolution (H/R = 0.47).

When the drillstring rotation was increased to Ω = 18.0 rad/s, it became possible to apply the epoxy technique and the sediment particles bed profile is shown in Fig. 2b. It is clear from this figure that a large amount of sediments was transported due to the drillstring rotation and deposited downstream of the annular space. However, the volume occupied by the sediments remains the same, indicating that the package of the sediment particles bed is the unchanged and the sediments were only displaced due to the velocity field created as a result of the rotation of the inner cylinder.

The movement of the sediment particles that was started by the drillstring rotation can aid the axial flow on the transport of the sediments, increasing the efficiency of the hole cleaning process. The change in the shape of the annular space can also interfere in the main velocity profile, affecting the cleaning performance as well. The sediment particles bed profile measured in this work can also be used as boundary condition to computational works in order to obtain the velocity field and acquire a better understanding of the process.

For an angular velocity Ω = 20.0 rad/s (Fig. 2c) more sediment particles were transported and a larger area that was initially occupied by sediments is filled only by the fluid. As in the previous case the cuttings removed from this region was transported downstream in the annular space but without changing the package of the sediment particles bed. For the kind of sediments used in this work and this rotation, the bed profile is different from the previous one and the axial velocity of the drilling fluid will consequently suffer a different influence of the bed form.

When the drillstring rotation was increased to Ω = 20.0 rad/s (Fig. 2d) a larger amount of cutting was transported but the effects it will have on the cleaning process needs to be investigated by modeling the flow in the annular space.

Figure 3 shows the results obtained for H/R = 0.74 (intermediate bed level). For velocities up to 10.0 rad/s no significant changes were noticed. When the velocity was increased to Ω = 12.0 rad/s (Fig. 3a) a small gap was formed downstream of the cylinder and no changes were noticed upstream. It indicates that the packing rate of the sediment particles bed increased, because the same amount of cuttings occupies a smaller volume of the annular space. The increase in the packing rate can difficult the process increasing the torque necessary to drill the well.

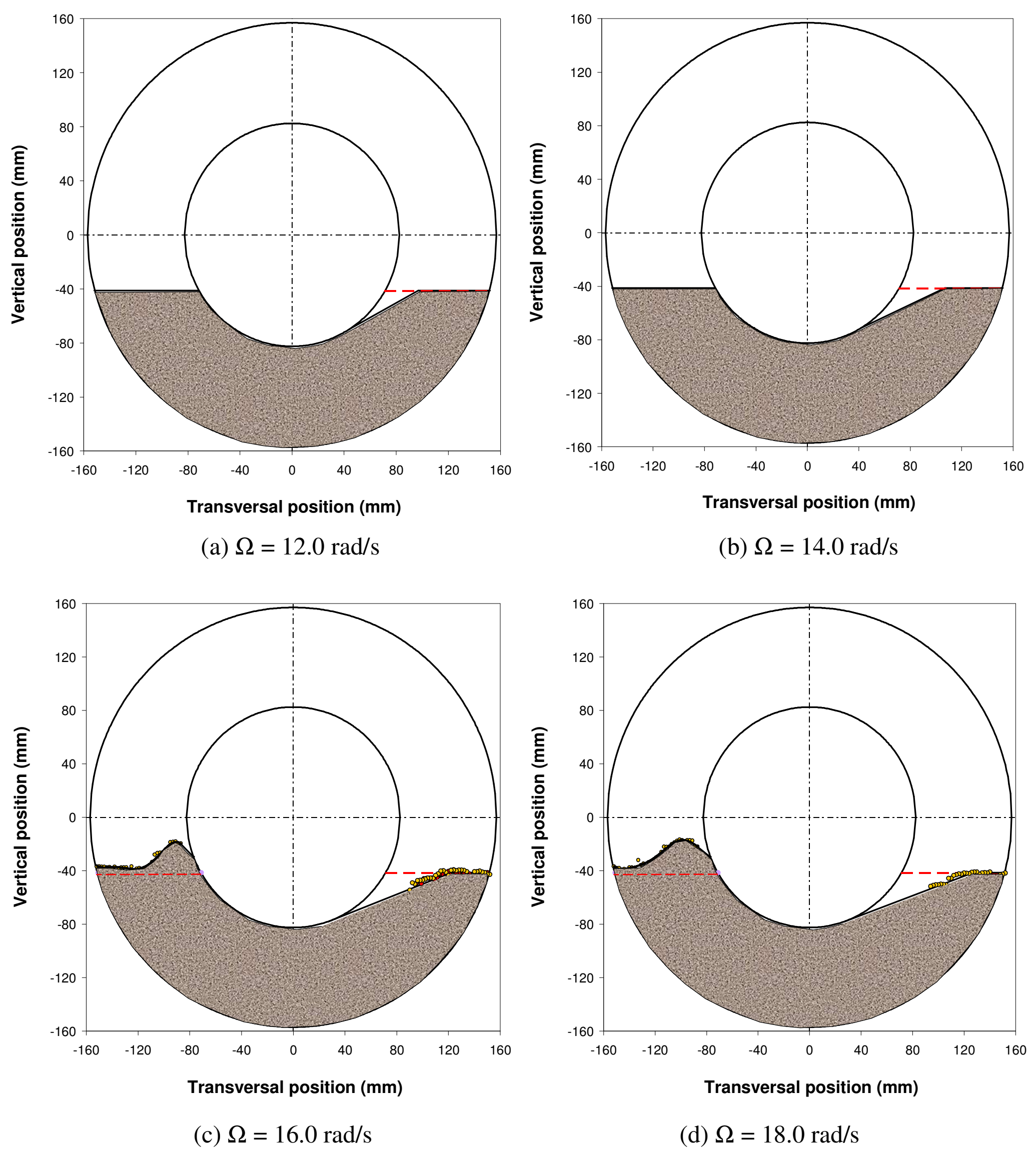
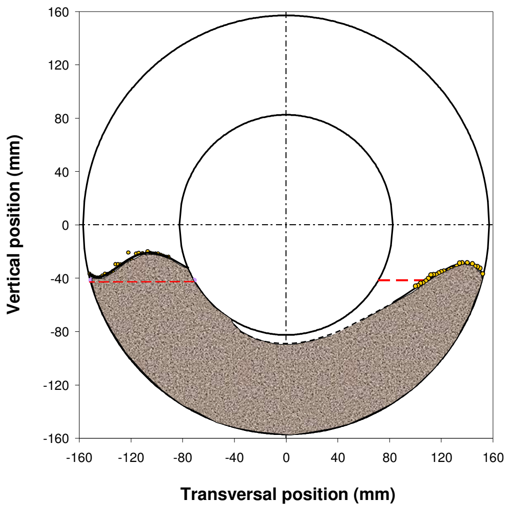
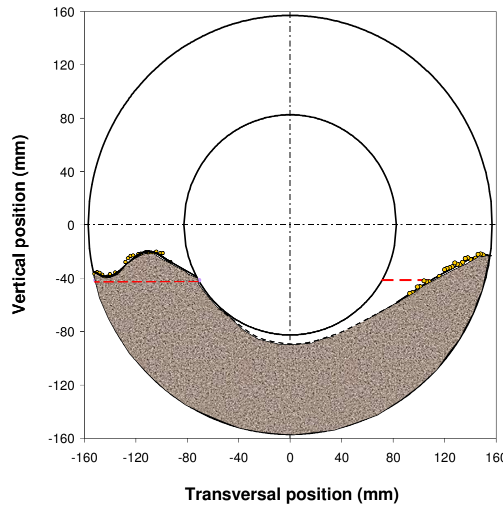


Figure 3. Influence of drillstring rotation on sediment particles bed evolution (H/R = 0.74).



(e) Ω = 20.0 rad/s



(f) Ω = 22.0 rad/s

Figure 3 (cont.). Influence of drillstring rotation on sediment particles bed evolution (H/R = 0.74).

The velocity of 14.0 rad/s was not sufficient to move the cuttings on the left side of the annular space but it increased the package of the sediment particles bed. For larger velocities, Fig. 3(c-f), the sediment particles start to move under the cylinder and deposit downstream in the annular space. In this case (H/R = 0.74), contrary to the previous (H/R = 0.47), the cylinder rotated clockwise.

According to Fig. 3c, due to the pile of sediment particles formed adjacent to the cylinder following the rotation direction, it is possible to conclude that the particles were moved in a small gap formed under the inner cylinder. This gap has the dimension of the mean particle diameter and when the cylinder stops it is filled with sediment particles. Although not presented here, the flow visualization endorses this finding because the sediment particles were seen to move freely under the cylinder.

For Ω = 18.0 rad/s, Fig. 3d shows that the sediment particles continues to be transported by the drillstring rotation and increase the size of the sediment particles pile downstream in the annular space. However, the decrease in the sediment particles volume upstream in the annular space is compensated by the increase in the sediment particles pile volume downstream, keeping the packing rate unchanged.

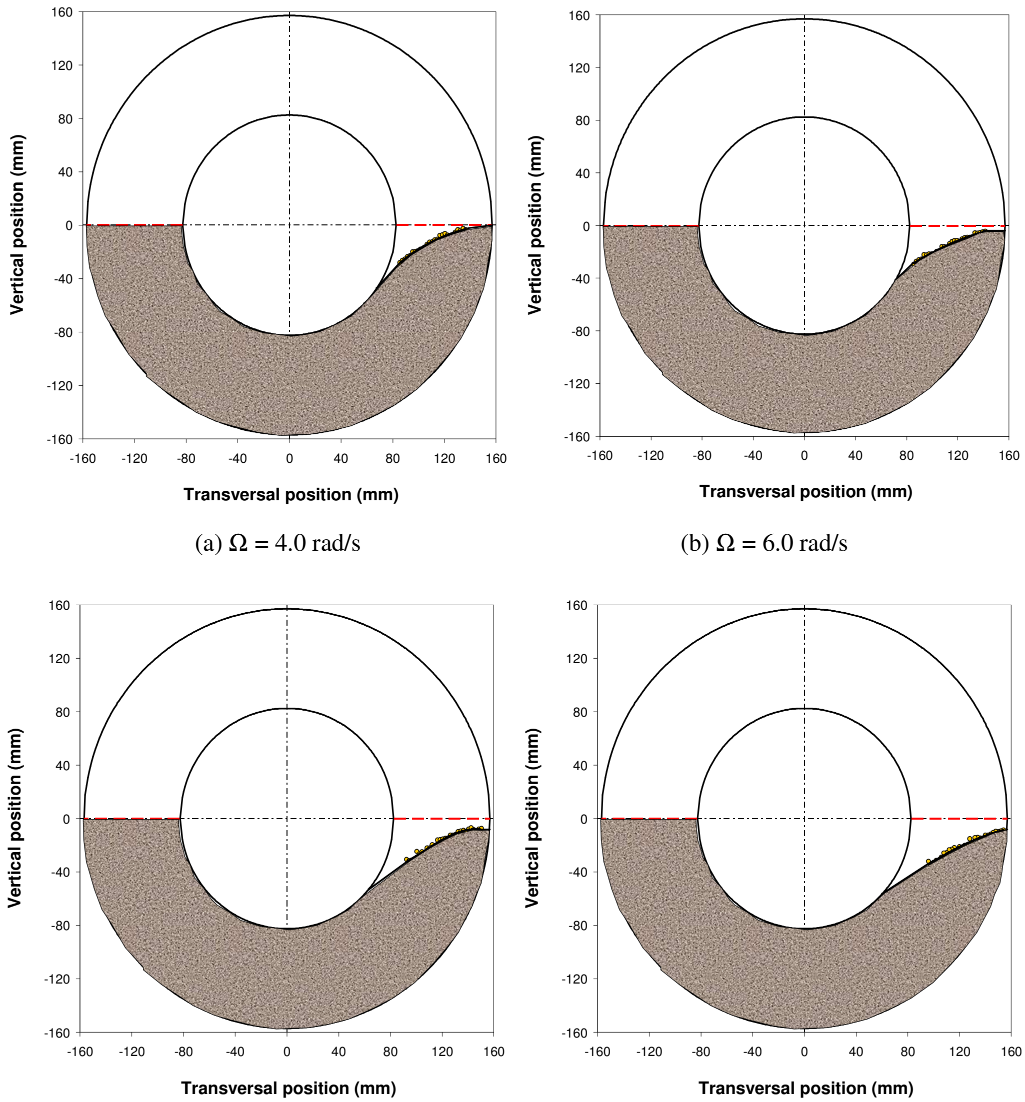
As the drillstring rotation increases even more (Fig. 3e and Fig. 3f), the sediment particles bed profile changes its form and increase the size of the gap under the inner cylinder, increasing the amount of particles transported by the drillstring rotation.

In the horizontal space between the inner and the outer cylinder the bed profile was measure using an ultra-sound system (the dots indicates the cuttings bed level measured by the sensor) but under the cylinder the gap was not sufficient to allow the measurement using the epoxy technique and the results shown are an approximation done by flow visualization and therefore are only qualitative.

For this bed level (H/R = 0.74), it can be concluded that for angular velocities up to 10.0 rad/s the drillstring rotation did not interfere on the sediment particles bed profile and all the transport has to be done by the axial velocity. For drillstring rotations of 12.0 rad/s and 14.0 rad/s a small increase in the packing rate of the sediment particles bed was noticed but the particles were not transported by the flow due to the inner cylinder rotation. And finally, for angular velocities above 16.0 rad/s the sediment particles start to be transported by the flow in the gap formed under the cylinder.

The results obtained for H/R = 1.0 (half of the volume in the annular space filled with sediment particles) are shown in Fig. 4 and Fig. 5. Figure 4 shows the results obtained for velocities between 4.0 rad/s and 10.0 rad/s and Fig. 5 shows the results for velocities between 10.0 rad/s and 20.0 rad/s. The angular velocity Ω = 22.0 rad/s was not evaluated due to limitations of the equipment.

As observed for the velocities of 12.0 rad/s and 14.0 rad/s in the previous case (H/R = 0.74), for velocities between 4.0 rad/s and 10.0 rad/s (Fig. 4) the package of sediment particles bed increased with the increase in drillstring rotation. This fact is represented by the decrease in the sediment particles volume upstream in the annular space and no change in the sediment particles bed level downstream. The package increase due to drillstring rotation is shown in Tab. 1.



(a) Ω = 4.0 rad/s (b) Ω = 6.0 rad/s

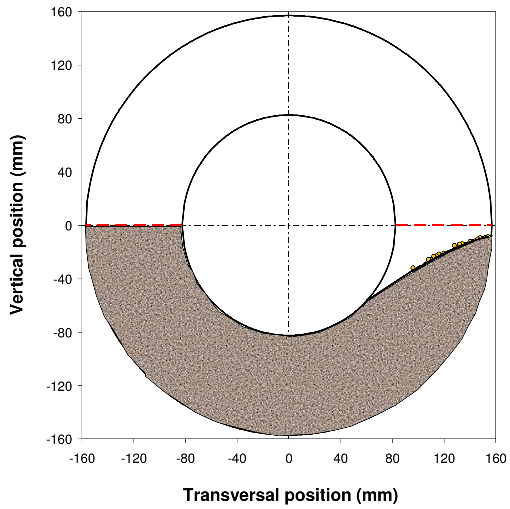
(c) Ω = 8.0 rad/s (d) Ω = 10.0 rad/s

Figure 4. Influence of drillstring rotation on sediment particles bed evolution (H/R = 1.0).

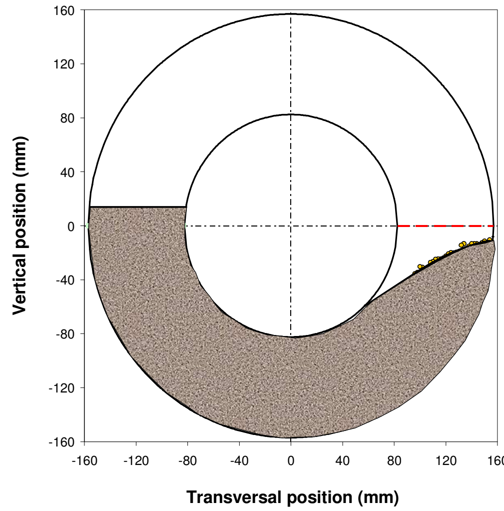
According to Tab. 1, as the drillstring rotation increases the inner cylinder tangential velocity increases which is obvious. But the tangential velocity of the inner cylinder caused by the drillstring rotation carried the cuttings that are in contact with it, forcing the cuttings against each other and decreasing the empty spaces in the sediment particles bed consequently increasing the compactness of the bed. A larger package increases the effort of the drillstring movement on the drilling process, making of it a harder task.

Table 1. Influence of drillstring rotation on compactness rate (H/R = 1.0).

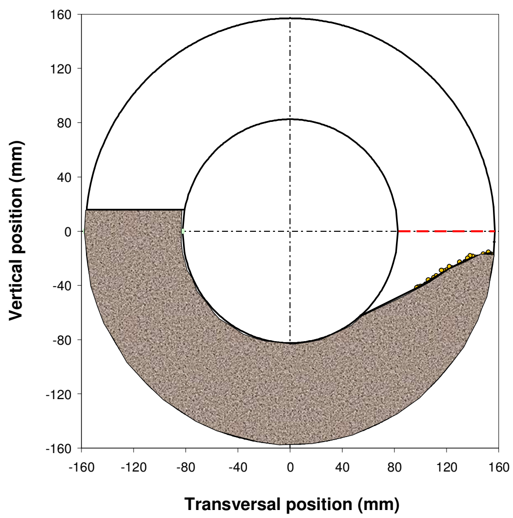
Drillstring angular velocity (rad/s)	Inner cylinder tangential velocity (m/s)	Packing rate (%)
4.0	0.33	3.12
6.0	0.50	3.87
8.0	0.66	5.67
10.0	0.83	6.77
12.0	0.99	3.48
14.0	1.16	5.04
16.0	1.32	4.07
18.0	1.49	3.84
20.0	1.65	2.48



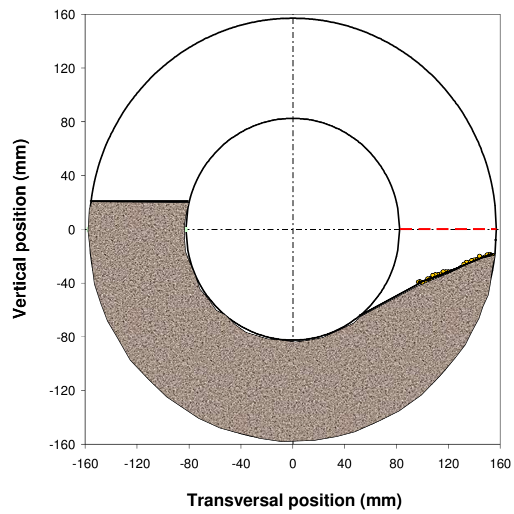
(a) Ω = 10.0 rad/s



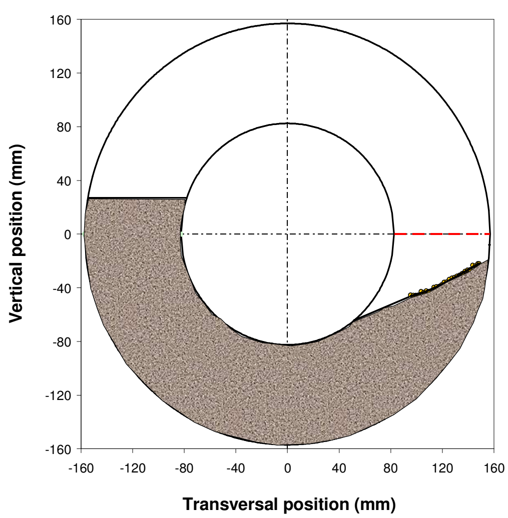
(b) Ω = 12.0 rad/s



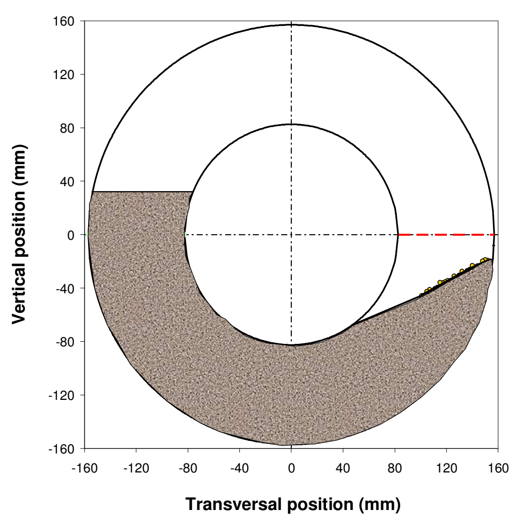
(c) Ω = 14.0 rad/s



(d) Ω = 16.0 rad/s



(e) Ω = 18.0 rad/s



(f) Ω = 20.0 rad/s

Figure 5. Influence of drillstring rotation on cuttings bed evolution (H/R = 1.0).

Figure 5 shows the results obtained for H/R = 1.0 and velocities between 10.0 and 20.0 rad/s. The velocity of 10.0 rad/s was discussed above and is repeated here only for reference.

When the velocity of the drillstring is increased to 12.0 rad/s (Fig. 5b) the sediment particles bed level decreased upstream, as notice previously for lower rotation velocities. However, the increase in the sediment particles bed level downstream was larger than the decrease observed upstream, leading to a decrease in the packing rate. Nevertheless, the packing rate observed for this experiment in particular was smaller than the expected, when compared to the results obtained for the other rotational velocities (Tab. 1b). This result should be analyzed with care and a duplicate of this experiment is being carried out.

According to Tab. 1b, as the drillstring rotation increases from 14.0 rad/s to 20.0 rad/s, the packing rate decreases, indicating that for rotational velocities larger than 14.0 rad/s the drill string is contributing to the movement of the sediment particles bed. However, as one can see from Fig. 5(b-f), the sediment particles bed downstream increased its level but continues even, showing that the cuttings bed were moved by the inner cylinder as it rotates and not transported due to the movement of the fluid (free movement of the cuttings).

4. Conclusions

Experiments were carried out to verify the influence of drillstring rotation on sediment particles entrainment and sediment particles bed profile. For the lower bed level evaluated (H/R = 0.47) the movement of the sediment particles started for a rotational velocity of 16.0 rad/s, while for the intermediate (H/R = 0.74) and higher (H/R = 1.0) bed levels, the movement started at rotational velocities of 12.0 rad/s and 4.0 rad/s, respectively. The decrease of the threshold velocity for the movement of the sediment particles was due to the contact of the inner cylinder with the sediments, which was bigger for larger values of H/R, causing a drag of the particles by the cylinder, increasing the packing rate. However, the free movement of the particles for H/R = 0.74 also occurred for a rotational velocity of 16.0 rad/s and for H/R = 1.0 the free movement of the particles was not noticed and the movement of the sediment particles was due to the contact with the cylinder and not due to the flow.

Instead of assist to the sediment particles entrainment, drillstring rotation can hinder the process for some rotational velocities, depending on bed level, due to the increase in the packing rate.

Since the flow pattern can be changed by the bed profile, the results presented herein can also be used as boundary condition to simulate the flow pattern in the annular space and shed some light on the transport process that occurs in an obstructed annular space.

Besides the parameters investigated in this work, an study that evaluates the influence of eccentricity of the drillstring, well inclination angle, rheological properties of the drilling fluid, and other sizes, shapes and densities of the sediment particles would contributes considerably to the improvement of the drilling process.

5. Acknoledgements

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