# DETERMINATION OF THRESHOLD SHEAR STRESS TO DRAG PARTICLES IN CUTTINGS BED

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***Abstract.*** *The efficient hole cleaning is still a challenge in the wellbore drilling for production of oil and gas. The critical point is the horizontal drilling that inherently tends to form a bed of sediment particles at the bottom of the well in drilling. And the erosion in cuttings bed depends mainly on the shear stress promoted by the flow of drilling fluid. Using an experimental assembly of a sedimented particle box in a system for circulation of fluids, composed of pump system, measuring equipment and supervisory, will seek to determine the shear stress required to drag in cuttings bed according to the fluid and particles properties. The area of observation consists of a box below the line of flow, for calibrated sand particles, in an acrylic duct with 6000x240x80mm. There is a camera to measure the drag of solids. The test starts with the pumps in low frequency and are made the increments. At each level of frequency are captured images of particles carried and it is records the established flow rate. The analysis of the processing of images is defined when the drag particle no longer be random and sporadic, and begins to be permanent. The shear stress was determined by the PKN correlation (by Prandtl, von Kármán, and Nikuradse) from the minimum flow rate necessary to drag. Results were obtained for the flow of water, water-glycerin solution 0,007Pa.s, and water-glycerin solution 0,011Pa.s.*

***Keywords****: shear stress, cuttings bed, horizontal drilling*

## 1. INTRODUCTION

The drag of solids by liquids is a phenomenon present in different systems, since the erosion of the bottom of rivers to industrial processes such as ore transport and drilling of oil wells. The solid naturally tend to deposit on the bottom forming a bed by the gravitational effect and the erosion of this bed depends on each system; of the characteristic of the solids, of the fluid, and of the flow.

The exploitation of oil fields demand high costs, of which a significant portion is attributable to the drilling process. The drilling process produce solid particles (cuttings) that can be deposited at the bottom of the annular region between the wall of the well and the drill string, as shown in Fig. 1. If the drilling fluid is not efficient to transport these solids may occur, for example, locking the column or, secondly, to fracture the formation. Currently consider that much of the time lost in unexpected events is associated with drill string locking and that a major cause is the inadequate removal of solids. (Costa *et al.*, 2008)

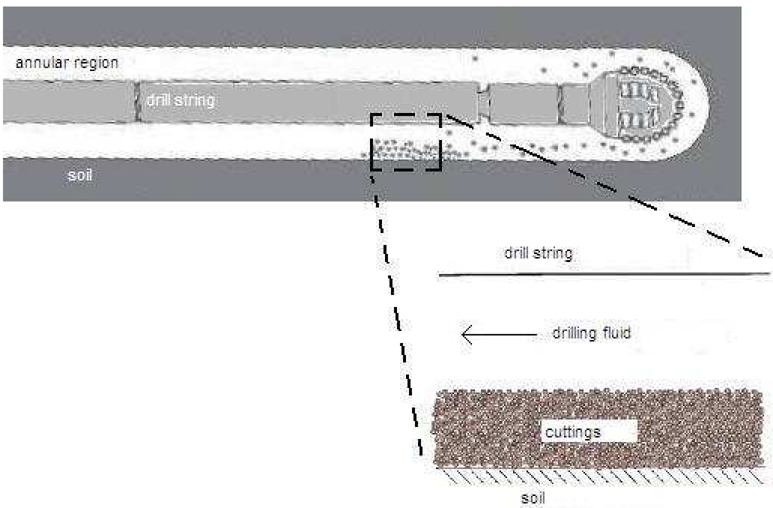


Figure 1. Drilling of high inclination

The directional drilling, widely used in the world, is the technique to intentionally deflect the trajectory of the vertical to achieve the target that are not directly below the surface of the utility installed. And a particularization of this technique is the horizontal drilling that permits to great the reservoir exposition and can enhancing the productivity of complex wells.

In the industrial process, the fluid is injected in the drillstring and returns in the annular space to the surface, bringing the solids, where these are separated and the drilling fluid is injected again.

The flow in the annular region of a horizontal well can be characterized by an homogeneous suspension, the solids uniformly dispersed or mixed with a concentration along the cross section, or by the deposition of solid stationary or mobile in the bottom of the well. (Martins, 1990)

The presence of a bed cuttings in the horizontal portion of the drilling represents the greater difficulty of cleaning of well in the fluid circulated process. As the erosion process occurs from particles deposited on the interface of bed with the drilling fluid, this may highlight the importance of the interfacial shear stress produced by the fluid flow.

This work proposes determine the critical shear stress capable of initiating the bed erosion process according to the properties of the fluid and the particles. This study is an extension of the paper presented by Loureiro, Siqueira and Martins (2006) and uses a looping as experimental apparatus controlled by supervisory system.

## 2. LITERATURE REVIEW

Caenn and Chilling (1996) discussed the characteristics and functions of the drilling fluid. The study informs that the majority of books and manuals about drilling fluid list 10 to 20 features that runs a drilling fluid to drill a well. And that, in general, the main functions are: drag cuttings and allow their separation on the surface, cool and clean the drill bit, reduce friction between the drillstring and the well hole, maintaining the stability of the well bore; keep solids in suspension; do not damage the formation, is not dangerous to the environment and people. The work noted that at each moment in the drilling process a function is more important than another. For large distances and horizontal wells, the features cleaning and maintaining the integrity of the well are generally considered more important.

Azar and Sanchez (1997), showed the influence and limitations of the relevant parameters in the transport of cuttings in the well drilling, including that although the flow rate is limited by the availability of hydraulic power equipment, the allowable current density and susceptibility the walls of the well to water erosion, it is the flow rate of drilling fluid the most relevant.

Silva and Martins (2002) developed a mathematical model for the analysis of resuspension of particles in horizontal annular ducts considering the influence of the shear stress.

Loureiro, Siqueira, and Martins (2006) obtained the minimum shear stress to drag cuttings in a bed using to experimental apparatus with controlled flow of water over a bed of particles sedimented.

## 3. METHODOLOGY

The objective is determining the shear stress produced by a particular fluid flow on the particles bed. The experimental assembly is used to measure the flow rate and the particles dragging. The alternative used to represent the physical phenomenon is a particle box in a rectangular acrylic duct (Fig. 2).

Figure 2. Experimental assembly

### 3.1. Governors Equations

The relevant dimensional parameters to the problem are the shear stress and flow average velocity, the gravity acceleration, fluid viscosity and density, the particles average diameter and density, and the duct equivalent diameter. From the Buckingham PI theorem (Fox and McDonald, 1995) is possible to obtain non dimensional groups for the problem physical using the functional Eq. (1):

$$\frac{\tau}{\rho u^2} = \Re\left( \frac{gD_l}{u^2} \quad \frac{\mu}{\rho u D_l} \quad \frac{d_p}{D_l} \quad \frac{\rho_p}{\rho} \right) \tag{1}$$

Where $\tau$ is the wall shear stress, $\rho$ is the fluid density, $u$ is the flow average velocity, $g$ is the gravitational acceleration, $D_l$ is the duct equivalent diameter, $\mu$ is the dynamic viscosity, $d_p$ is the particles average diameter, and $\rho_p$ is the particle density.

It is the effect of the rectangular duct in developed fully turbulent flow using the Eq. (2) for the approximate calculation of the equivalent diameter as proposed by Jones Jr. (1976) *apud* Rohsenow *et al.* (1998).

$$D_{l.} = \frac{2}{3} D_{h.} + \frac{11}{24} \alpha \cdot (2 - \alpha) \tag{2}$$

Where $D_{h.} = 4\frac{A}{P}$, and $\alpha = \frac{h}{b}$.

The parameter $D_h$ is the hydraulic diameter, $\alpha$ is the aspect rate, $A$ is the duct cross session area, $P$ is the duct cross session perimeter, $h$ is the rectangular duct height, and $b$ is the rectangular duct width.

The criteria to determine threshold shear stress uses the flow rate value when the erosion bed process is continuous, and no more random. Then the Reynolds number is obtained. The PKN correlation for developed fully turbulent flow was proposed by Prandtl (1944), von Kármán (1934), and Nikuradse (1932) *apud* Rohsenow *et al.* (1998), and is presented in the Eq. (3) to calculate the Fanning friction factor *f*.

$$\frac{1}{\sqrt{f}} = 1{,}7272 \ln\left(\mathrm{Re}\sqrt{f}\right) - 0{,}3946 \tag{3}$$

The wall shear stress is obtained by Fanning friction factor definition (Rohsenow *et al.* 1998), as in Eq. (4):

$$f = \frac{\tau}{\rho u^2 / 2} \tag{4}$$

### 3.2. Experimental Assembly

The acrylic duct length is 6 m, the wide is 240 mm, and the height is 80 mm. The sedimented cuttings box is mounted 4,8 m from the entrance of this duct, has the same width, length of 480 mm and depth of 40 mm. The sedimented bed is mounted in this box with sand particles of calibrated size (Fig. 3).

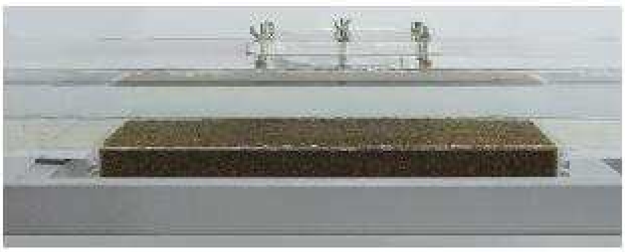

Figure 3. Cuttings box

The flow is induced by gradient of pressure through two centrifugal pumps and one helicoidal pump. The installed valves permit the pumps operation on single or parallel. A box of edges equals to 375 mm located before the acrylic duct entrance reduces the entrance turbulence. An internal deflector prevents the directional flow jet from the pipe to the acrylic duct.

Above the observation area is installed an analogic monochromatic progressive scan camera to acquire particles flow images during the sedimented bed erosion. These images are then processed by the National Instruments Vision software allowing measure the dragging.

The assembly has a Coriolis flow rate meter, a pressure meter, and a dedicated computer to run a supervisory system that control the three pumps by drives, and permits to view the valves status and recording the measurements of fluid flow rate, system pressure and pumps rotation.

### 3.2.1. Experimental Procedure

Initially the bed of particles is leveled in the box without fluid. The level of particles is in the same plane of duct surface, so there is not step upstream and downstream from bed region. The looping is completed of fluid test slowly to do not change the surface. All valves of principal circuit are opened and one pump is turned on in low rotation to throw away the air bubbles.

The measurements are started up with two pumps with low rotation and then are made increments. At each frequency level are captured images of the flow after the cuttings box. Measurements of fluid flow rate, pipe pressure and pumps rotation are continuously displayed on the screen of the supervisory system and these data are pos-processed in the end of test.

After test, circuit should be emptied, the particles must be removed, and the procedure repeated for each different size of particles.

### 3.2.2. Image Processing

Before start up the test, a reference image should be acquired for image processing, Fig 4(a). A sequence of 30 images is captured for each flow rate. The images are acquired two minutes after change the pumps rotation to permit flow stabilization. After test, the images are processed in the NI Vision Assistant software using a sequence of filters. An example of image processing script used is shown in the Fig 4. The processing sequence of Fig 4 is: (a) reference image, (b) original image, (c) resulting of the original image minus reference image (d) image converted from 16 to 8 bits; (e) brightness adjust, contrast and gamma; (f) attenuated the changes in light intensity, (g) Selected the threshold limits; (h) ) image converted from 8 to 1 bit; (i) binary information reversed.

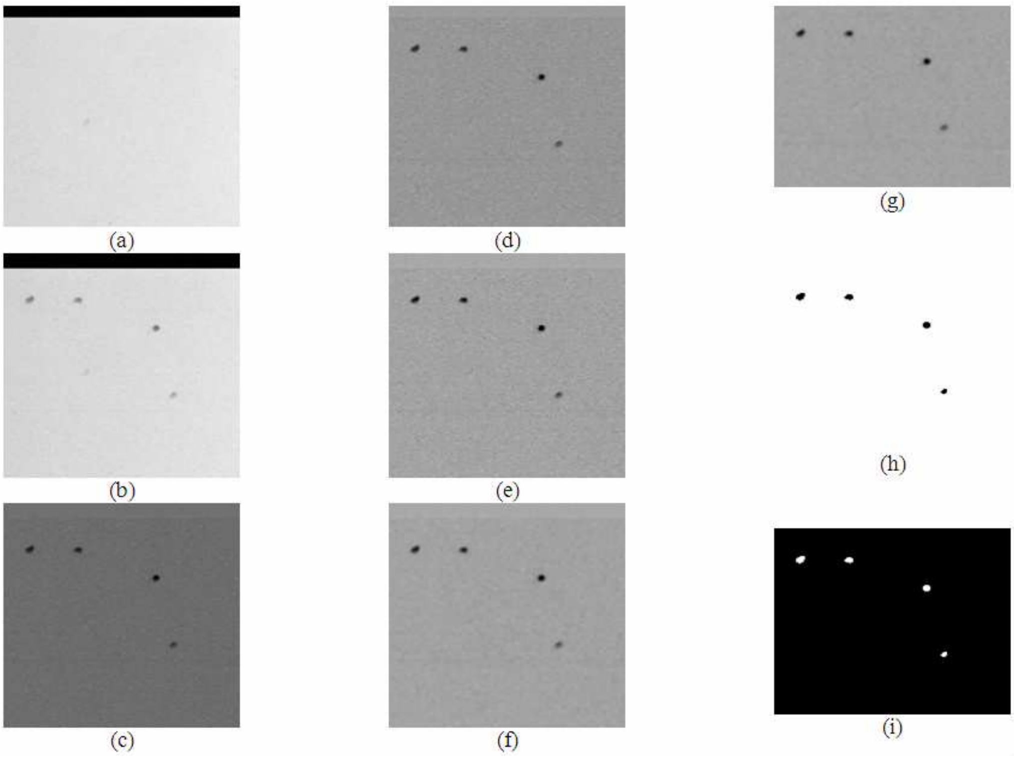


Figure 4. Image Processing

The processing result is the particles area present in each image on pixel unit. An average of particles area is taken from 30 images to indicate a parameter of dragged particles in each flow rate step. A criteria is adopted to define when the process of particles dragging is permanent, and no more random.

## 4. RESULTS

The experiments were performed to different particles classes with geometrical characteristics shown in Table 1. Those characteristics are obtained from images processing. The circularity 1 indicate spherical particles and 0 flat.

Table 1. Particles geometric characteristics

| Class | Mean diameter (m) | Circularity |
|---|---|---|
| 1 | 0,0007 ± 0,0001 | 0,88 ± 0,05 |
| 2 | 0,0008 ± 0,0001 | 0,86 ± 0,09 |
| 3 | 0,0010 ± 0,0001 | 0,90 ± 0,06 |
| 4 | 0,0012 ± 0,0002 | 0,85 ± 0,09 |
| 5 | 0,0018 ± 0,0002 | 0,85 ± 0,09 |
| 6 | 0,0022 ± 0,0004 | 0,93 ± 0,05 |

After analyze the images and numerical data generated from the image processing, is possible to define the minimum flow rate that the process of particles dragging is permanent. This value is obtained from mean particle area derivate in function of flow rate.

The minimum flow rate required for the erosion of a sedimented bed was made for each particles class for three Newtonian fluids: water, water-glycerin solution at 0,007 Pa.s and water-glycerin solution at 0,011 Pa.s. Table 2 presents the values of minimum flow rate for each mean diameter of particles presented in the sedimented bed and Newtonian fluid.

Table 2. Values of minimum flow rate to start up the erosion process of the sedimented bed

| Class | Water flow rate (kg/s) | Water-glycerin solution to 0,007 Pa.s flow rate (kg/s) | Water-glycerin solution to 0,011 Pa.s flow rate (kg/s) |
|---|---|---|---|
| 1 | 5,03 | 7,06 | 7,34 |
| 2 | 5,31 | 7,35 | 7,68 |
| 3 | 5,66 | 7,57 | 8,00 |
| 4 | 6,16 | 7,96 | 8,34 |
| 5 | 7,68 | 8,67 | 9,00 |
| 6 | 7,93 | 9,09 | 9,66 |

From presented equations, like PKN correlation, and fanning factor, the shear stress required to start up the erosion process of the sedimented bed is shown in Table 3.

Table 3. Values of minimum shear stress to start up the erosion process of the sedimented bed

| Class | Water $\tau$ (Pa) | Water-glycerin solution to 0,007 Pa.s $\tau$ (Pa) | Water-glycerin solution to 0,011Pa.s $\tau$ (Pa) |
|---|---|---|---|
| 1 | 0,160 | 0,401 | 0,472 |
| 2 | 0,177 | 0,430 | 0,511 |
| 3 | 0,198 | 0,453 | 0,549 |
| 4 | 0,231 | 0,494 | 0,589 |
| 5 | 0,342 | 0,574 | 0,674 |
| 6 | 0,363 | 0,624 | 0,763 |

The graph in Figure 5 shows the influence of particle diameter on the values of minimum shear stress to drag particles in cuttings bed for the three the fluids tested. The values of minimum shear stress increase with particle diameter for the three fluids. This means that a bed of larger particles diameter require higher minimum shear stress for erosion in any of viscosities tested that a bed of smaller particles diameter.

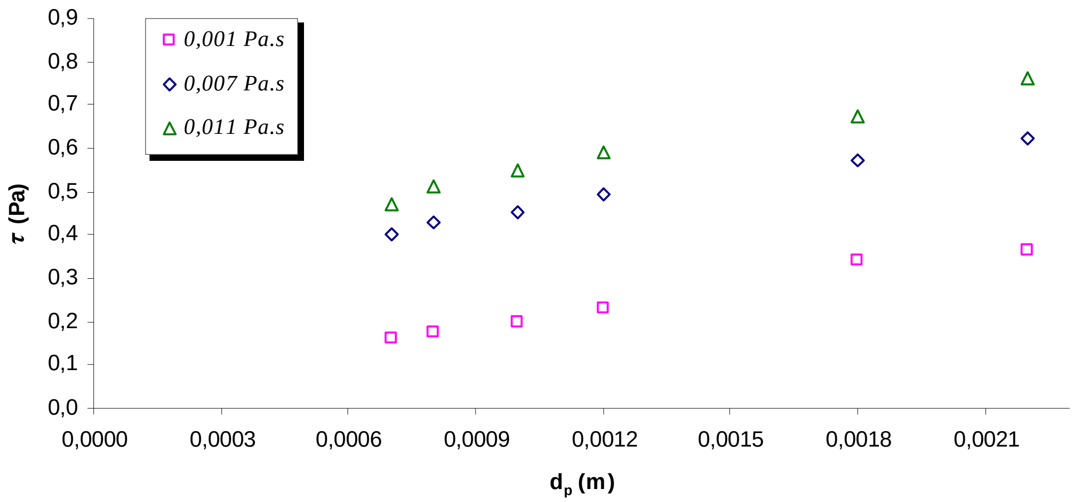


Figure 5. Influence of particle diameter at the threshold shear stress

The Figure 6 shows the variation of dimensionless threshold shear stress depending on the dimensionless diameter of bed particles. In the Fig. 6 we observe that the threshold shear stress tends to vary linearly with the diameter of particles, as in Eq. (5), that is interdependent of the characteristic of fluids. The legend of Figure 6 presents the density ratio of cuttings by the fluid.

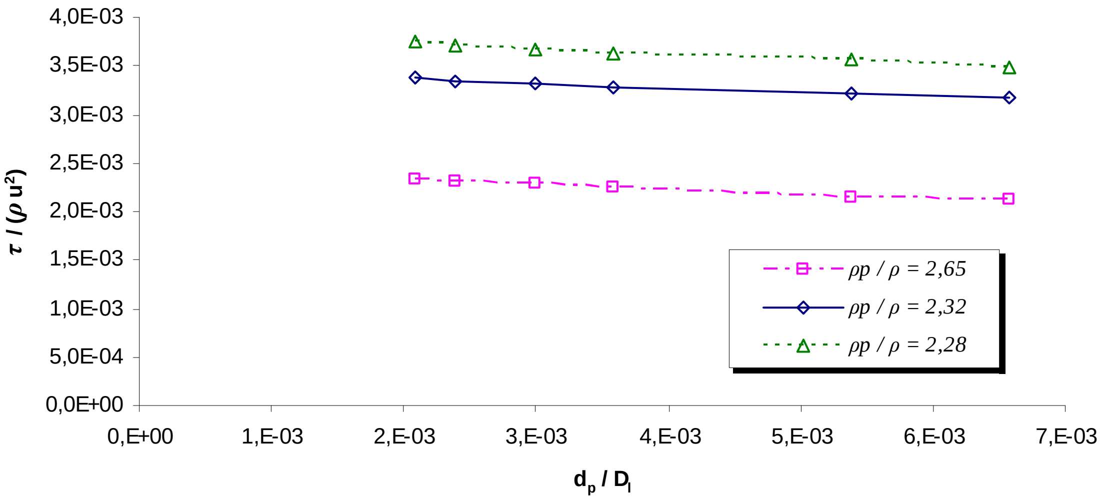


Figure 6. Dimensionless variation of threshold shear stress for particle diameter

$$\frac{\tau}{\rho u^2} = m\left(\frac{d_p}{D_l}\right) + n \tag{5}$$

Where:

$$m = -6{,}56 \cdot 10^{-1}\left(\frac{\rho_p}{\rho}\right)^2 + 3{,}25\left(\frac{\rho_p}{\rho}\right) - 4{,}05 \tag{6}$$

$$n = 1{,}89 \cdot 10^{-2}\left(\frac{\rho_p}{\rho}\right)^2 - 9{,}71 \cdot 10^{-2}\left(\frac{\rho_p}{\rho}\right) + 1{,}27 \cdot 10^{-1} \tag{7}$$

Where $\rho_p$ is particle density, and $\rho$ is the fluid density.

Figure 7 shows the influence of Reynolds number in minimum shear stress to start the process of drag particles in cuttings bed. It is presented threshold points to drag the six classes of particles for three Newtonian fluids, where the point of lower shear stress, for the same fluid, corresponds to the smallest particle diameter and the others points correspond to increasingly others classes of particles diameter. The erosion process start up, for the same class of particles, in the flow of higher Reynolds number for fluid of lower viscosity. All flows tested in the experiment were turbulent. Laminar flows were not studied.

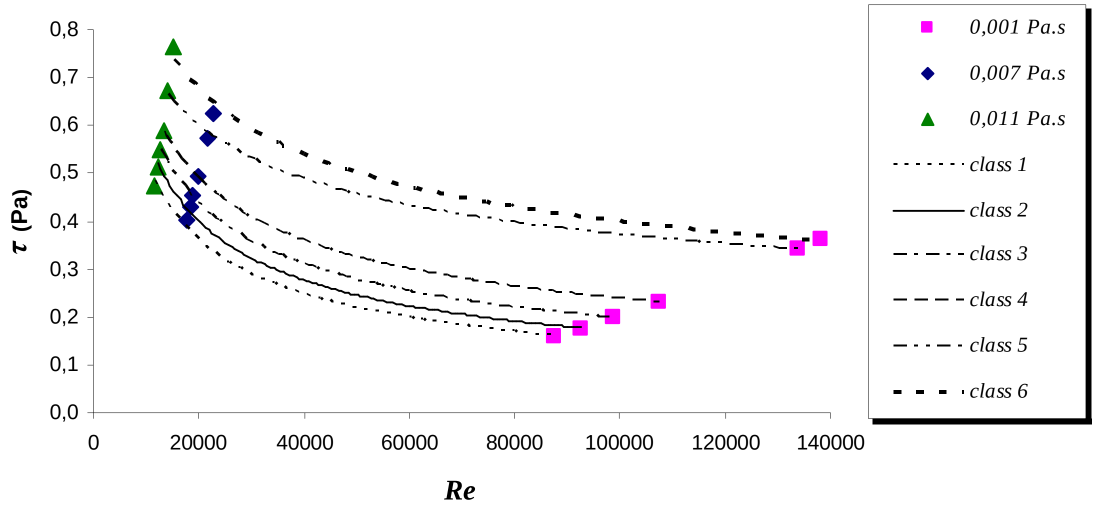


Figure 7. Influence of Reynolds number at the threshold shear stress

Figure 8 shows the variation of dimensionless minimum shear stress in terms of relations of viscous forces and inertia matching. In this graph it was possible to obtain a same trend curve for dimensionless minimum shear stress in function of flow considering different particles classes, and characteristic of the fluids and particles. The trend curve is presented in the Eq. (8).

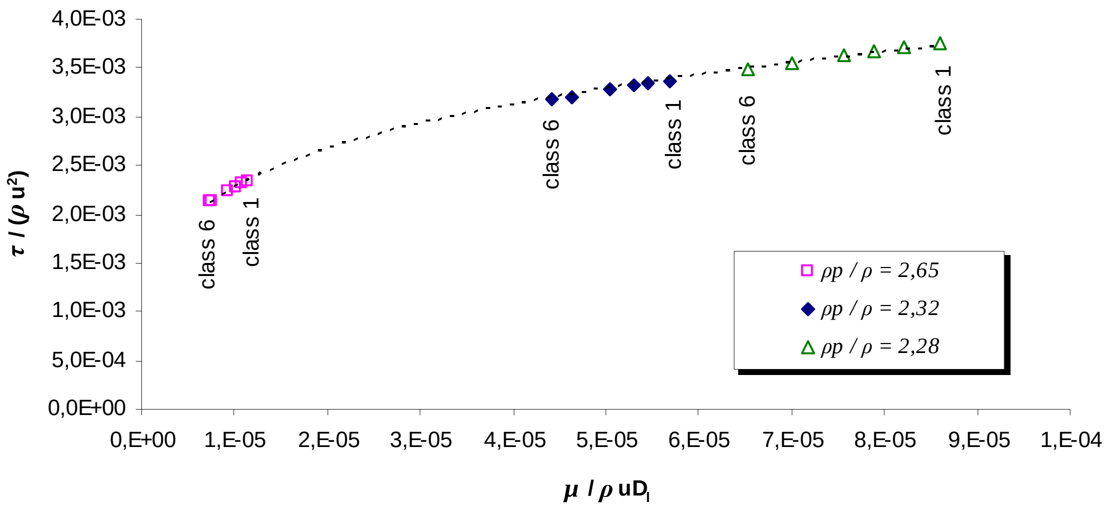


Figure 8. Dimensionless minimum shear stress in function of Reynolds number

$$\frac{\tau}{\rho u^2} = r\left(\frac{\mu}{\rho u D_l}\right)^2 + s\left(\frac{\mu}{\rho u D_l}\right) + t \qquad (8)$$

Where:

$$r = -1{,}09 \cdot 10^7\left(\frac{\rho_p}{\rho}\right)^2 + 4{,}89 \cdot 10^7\left(\frac{\rho_p}{\rho}\right) - 5{,}47 \cdot 10^7 \qquad (9)$$

$$s = 2{,}20 \cdot 10^{1}\left(\frac{\rho_p}{\rho}\right)^2 + 6{,}95 \cdot 10^{1}\left(\frac{\rho_p}{\rho}\right) - 2{,}54 \cdot 10^{2} \qquad (10)$$

$$t = 8{,}61 \cdot 10^{-3}\left(\frac{\rho_p}{\rho}\right)^2 - 4{,}47 \cdot 10^{-2}\left(\frac{\rho_p}{\rho}\right) + 5{,}95 \cdot 10^{-2} \qquad (11)$$

## 5. CONCLUSION

This work studied the erosion of a sedimented particles bed by the flow of Newtonian fluids. The experimental setup designed with acrylic allowed the visualization of the particles drag's to evaluate the physical phenomenon qualitative and quantitatively. For all flow was analyzed the influence of the diameter of the bed particles, and the Reynolds number.

It was concluded that the shear stress to start up the erosion process is function of the particles diameter, and fluid properties. For smaller mean diameter of particles, it is necessary a lower shear stress to start up the erosion process of the bed. In other words, the erosion of a settled bed is easier when the bed is made up of particles of smaller diameter, according to the characteristics of the particle size.

For all concentrations of tested fluids, the data also showed the same decreasing trend curve of the minimum shear stress to start up the erosion process with an increasing the Reynolds number. So, for the universe of particles and fluids tested, the increase of flow turbulence facilitates the erosion of the sedimented bed.

The obtained flow rate results were used to determine the minimum shear stress required to start up the erosion process of cuttings bed for each particle diameter.

These values can be applied to problem of horizontal wells drilling for the same particles sizes studied, based on the assumption that the erosion process is dependent only on shear stress.

The effect of non-Newtonian fluid with yield-stress is being studied in this experiment and will be presented in future works.

## 6. ACKNOWLEDGEMENTS

This research was possible due to the financial support of ANP, the Brazilian Petroleum Agency, FINEP (Financiadora de Estudos e Projetos), MCT, the Brazilian Ministry of Science and Technology, through PRH29-ANP/MCT (Programa Institucional da UFES para o Setor Petróleo e Gás), FAPES, and UCL.

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