

Experimental Determination of Particle Sedimentation Velocity in Opaque Drilling Fluids

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Abstract

Cuttings sedimentation velocity is a variable which directly impacts hole cleaning and consequently the drilling performance of complex wells.

The fluid capacity of keeping solids in suspension while the pumps are off is also a critical issue. These aspects add complexity to the fluid rheology design, especially when drilling in narrow operational window scenarios.

The literature presents extensive experimental studies in the factors influencing particle settling in Newtonian and non Newtonian fluids. Most studies are focused on visualization techniques which are limited to transparent fluids. Drilling fluids, on the other hand, are generally opaque not allowing sedimentation experiments.

Correlations developed with transparent fluids with equivalent rheological profiles normally do not reproduce gelation properties. The present work presents experimental results of particle sedimentation in non Newtonian fluids obtained by ultra sound measurements which are compared with results obtained from image processing techniques.

Particle size, shape and density effects were evaluated and the comparison of results indicate good agreement between the techniques.

Introduction

Recently one can observe major evolution of the oil industry in the Brazilian scenario. This evolution provided the breakthrough in this technological area and consequently the increasing of oil production. Thus, the drillings can be made in vertical or horizontal wells, requiring more and more specific fluids.

In the drilling, the fluid is pumped from a drilling unit to the well by a drill string with a drill at its end. The fluid flows through the interior of column, through drill and returns by a void region between the column and the well. The cuttings originated in drilling are then transported by a fluid through the annular region to the surface where it can be separated from the fluid in the equipment treatment and sent for proper disposal. The fluid recovered after treated, returns to the process.

As the drilling is carried out in several phases characterized by different diameters drilled, possibly operational arrest occurs for casing and cementing this new

phase of the well. At this point, the fluid flow is interrupted and it is necessary for the drilling fluid to become gels to prevent the cuttings from precipitating and obstructing the drill, avoiding a collapse of the system.

Currently, drilling fluids consist of complex mixtures of solids, liquids and gases. They can assume aspects of suspension, emulsion or colloidal dispersion, depending on the physical state of the components. They must be specified to promote rapid and safe operation with some special features [1]. They are indispensable to the drilling step because in addition to its primary function of carrying the generated cuttings to the surface, they still cool and lubricate the drill string and the drill, stabilize the well walls and have the cost compatible with the operation.

During the process of drilling oil wells, sediments generated by the drill are formed, known as cuttings. The transport of these cuttings to the surface via fluid has been the major concern of this area, since an inefficient cleaning process may cause well problems preventing from continuing of the operation.

The cleaning of the well depends on fluid parameters (density, rheology) and process (sedimentation velocity, geometry of the particle, flow).

The sedimentation velocity is defined as the speed at which the particles settle within a fluid due to its density, weight, size and geometry [2]. To determine the deposition velocity of particle is necessary to know the diameter of the particle, the drag coefficient of the particle and Reynolds number.

This work has as main goal exhibit the ability to determine the sedimentation velocity of regular and irregular particles in Newtonian and non Newtonian fluids by the technique of ultrasound, comparing it with technique of capturing and processing image, so its validation can be made. The big motivation for using this technique is the opacity based drilling fluids, mostly because it does not allow the use of the technique of capturing and processing image for evaluation of the sedimentation velocity particles.

Theoretical approach

According to Ataide et al. [3], where a particle of diameter “ d ” and density “ ρ_s ” falls under the gravity “ g ” in a stationary viscous fluid in an infinite medium (neglecting effect of rigid

boundaries and population or concentration), it moves rapidly to achieve balance between three forces: buoyancy (F_e), weight (P) and drag (F_a), then reaching a speed constant, called the terminal velocity (settling velocity). The forces acting on the particle are shown in Figure 1.

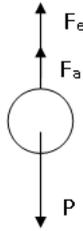


Figure 1. Forces acting on the accelerated motion of sphere in a stagnant fluid.

Performing a balance between the forces we get:

$$\sum F = P - F_e - F_a \quad (1)$$

The small particles are accelerated rapidly and reach a terminal velocity v_t ($dv/dt=0$), where the drag force is balanced by the apparent weight ($P - F_e$), and is called F_a . For a sphere moves under a fluid in a uniform rectilinear motion, when $\Sigma F = 0$, the equation of motion becomes:

$$F_a = \frac{\pi}{6}(\rho_s - \rho)gd^3 \quad (2)$$

Even establishing the equation of motion, Equation 2 cannot obtain the terminal velocity, then being able to use dimensional analysis to obtain the velocity of sedimentation. Dimensional analysis, applied to the study of particle dynamics isolated has the following similarity condition:

$$C_D = f\left(Fr^2, Re, \frac{\rho_s}{\rho}\right) \quad (3)$$

Where C_D is the drag coefficient; Fr is the number of Froud; Re is the Reynolds number and ρ_s/ρ is the ratio of the density of the particle and the density of the fluid. For this paper the number of Froud is disregarded due to the greater importance of the Reynolds number in the settling process. The drag coefficient and Reynolds number are defined from Equation 4 and Equation 5.

$$C_D = \frac{4}{3} \frac{(\rho_s - \rho)gd}{\rho v_t^2} \quad (4)$$

$$Re = \frac{\rho v_t d}{\mu} \quad (5)$$

Where the “ d ” is the particle diameter; “ v_t ” is the terminal velocity of the particle; “ ρ ” is the density of the fluid and “ μ ”

is the viscosity of the fluid.

It is known that the sedimentation velocity of the sphere appears in both the drag coefficient (C_D) as the Reynolds number (Re). Thus, an iterative method to obtain the value of this velocity is required.

Haider and Levenspiel [4] proposed a correlation to predict the value of C_D for spheres, Equation 6, and for irregular particles, Equation 7, which φ is the sphericity of the particle.

$$C_D = \frac{24}{Re} \left(1 + 0,1806 Re^{0,6459}\right) + \frac{0,4251}{1 + \frac{6880,95}{Re}} \quad (6)$$

$$C_D = \frac{24}{Re} \left[1 + [8,1716 \exp(-4,0655\varphi)] \times Re^{(0,0964 + 0,5565\varphi)}\right] \dots \quad (7)$$

$$\dots + \frac{73,69 Re \exp(-5,0748\varphi)}{Re + 5,378 \exp(6,2122\varphi)}$$

The Particle Shape Factor

The characterization of a particle by its shape is not easy, due to the difficulty of comparing the irregular forms. Knowing how the geometric particle shape influences its sedimentation velocity is of the utmost importance for the chemical processes, in particular for cleaning oil wells.

Wadell [5] introduced a correction factor for the shape of the particle called sphericity, defined by Equation 8:

$$\varphi = \frac{A_s}{A_p} \quad (8)$$

Where:

φ is the sphericity;

A_s is the surface area of a sphere of the same volume of the particle;

A_p is the surface area of the particle.

Thus, sphericity is a satisfactory criterion to determine the shape of an irregular particle.

Table 1, taken from Chhabra and Richardson [6] shows various shapes of particles and their sphericities.

Table 1. Typical values of sphericity.

Particle	Sphericity
Sphere	1
Cube	0,806
Cylinder $l/d=1$	0,873
Cylinder $l/d=10$	0,579
Cylinder $l/d=20$	0,471

Experimental Apparatus and Method

The method is divided into two steps. The first step consists on determining the geometrical characteristics of the particles and the properties of the fluid, while the second consists on determining the sedimentation velocity.

Geometric Particle Characterization

For the tests with regular particles stainless steel spheres ($\rho_s=7850 \text{ kg/m}^3$) and glass ($\rho_s=2600 \text{ kg/m}^3$) with diameters ranging from 3 to 10mm, smooth and spherical, acquired for the experiment were used.

Irregular particles isometric were also acquired, cubes and cylinders, made of steel ($\rho_s=7850 \text{ kg/m}^3$) and aluminum ($\rho_s=2700 \text{ kg/m}^3$), with dimensions varying from 3 to 15 mm.

The geometric particle characterization was performed by measuring the dimensions of each particle with a caliper and the density of each particle was determined by calculating the volume and measurement of their mass.

Description of the Fluids

The main Newtonian fluid used in the experiments was silicon oil ($\rho_0=980 \text{ kg/m}^3$) with viscosity about 1000 cSt. This fluid is suitable for testing since temperature influences little its viscosity.

However, to achieve high Reynolds numbers, glycerol solutions were also used because of its low viscosity.

As non-Newtonian fluids, Carbopol solutions were prepared and used in the test.

Ultrasound

The method of ultrasound consists in generating, transmitting and amplifying an electrical pulse which is converted into the ultrasonic pulse by a transducer. The sequence of pulses form an ultrasonic beam that is aligned to another receiving transducer, the same specification as Figure 2.

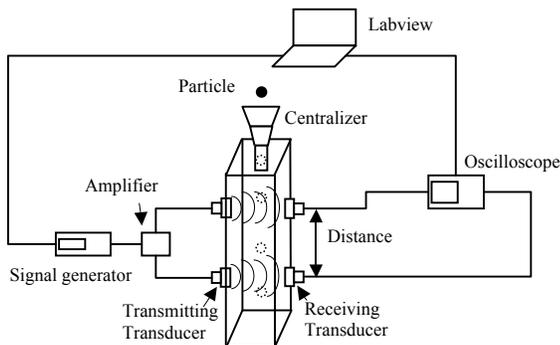


Figure 2. Arrangement of the measuring system of the particle settling velocity.

The ultrasonic signal travels through the walls of the acrylic tank with 1.20 m tall and square edged 0.2 m base, and runs through the fluid reaches the sensor reception. The receiving transducer converts mechanical pulses into an electrical signal that is captured by an oscilloscope (Agilent 6000 Series MSO). The oscilloscope recorded the wave form converted by the receiving transducer and sends an application developed in Labview, in real time.

The experiment by ultrasound is all controlled by a supervisor in Labview, Figure 3.

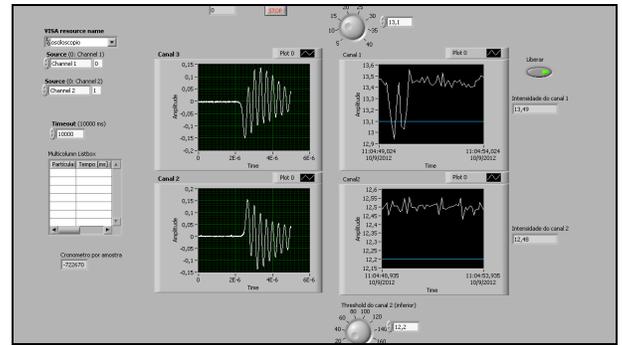


Figure 3. Screen supervision of measuring sedimentation velocity ultrasound system.

When the particle crosses the first ultrasonic beam, the timer starts. Then, when the particle crosses the second ultrasonic beam, the timer closes. Knowing the distance between the ultrasonic beam, and with the value obtained from the speed can be calculated.

To validate the technique of ultrasound was necessary to adapt the supervisor in Labview to communicate with a CCD camera via trigger, allowing the evaluation of the particle detection by ultrasound transducers and confirmation of the speed of the particle image. In order to ensure the measurement between the transducers, a structure was made of acrylic, so that the distance between the centers of the transducers were $10.00 \pm 0.05 \text{ cm}$, and can be exemplified by Figure 4.

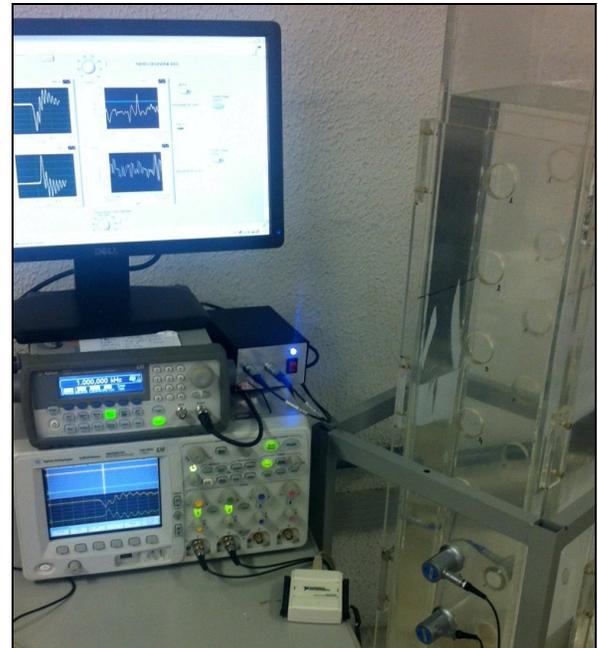


Figure 4. Mounting the experiment measuring the settling velocity by ultrasound.

In order to obtain a standard testing procedure 30 spheres releases of different diameters, steel and glass, as well isometric particles, cubes and cylinders of steel and aluminum have been dropped.

Results and Discussion

First, glass beads and steel were used to validate the technique of ultrasound in silicone oil and also in glycerol solutions to achieve different values of Reynolds. The results of the sedimentation velocity of spheres by ultrasound were compared with those obtained by the technique of capture and image processing. The two techniques analyzed showed spherical particles having the same behavior as shown in Figure 5, allowing validate the ultrasound technique according to Equation 6.

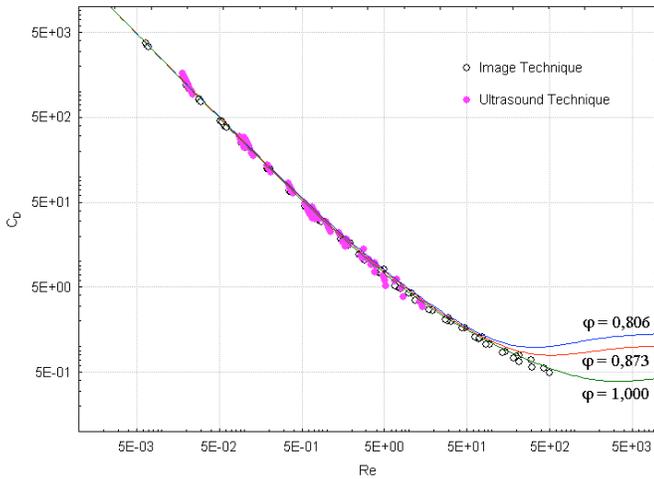


Figure 5. Drag coefficient as a function of Reynolds number for spheres of different sizes and materials.

The results in Table 2 show the average speed acquired by the ultrasonic transducers for 30 releases of each spherical particle. The mean square error was calculated in relation to the theoretical speed of each particle, according to Equation 6, proving that the technique of ultrasound can determine the settling velocity of spheres with a satisfactory error. However, it was possible to detect that the error is influenced by the velocity of the particle. This shows that the technique has a usage limit.

Table 2. Results of the sedimentation velocity of spherical particles by ultrasound method.

Particle	Diameter (mm)	Average Speed (cm/s)	Error
Steel	3,00	3,3491	4,58%
Steel	6,35	13,375	5,19%
Steel	8,00	20,472	9,45%
Glass	3,00	0,7213	7,41%
Glass	6,35	3,2743	2,36%
Glass	7,93	4,8772	3,31%
Glass	10,0	7,3546	4,68%

To validate the technique of ultrasound for irregular particles, cubes and cylinders were cast in silicone oil and also in glycerol solutions. The velocities were obtained by both the

technique of capturing and processing images as the technique of ultrasound, to make possible a comparison with the literature.

The graph of Figure 6 shows the results of the drag coefficient and Reynolds number obtained by the sedimentation velocity of cubes obtained by the two techniques. It is observed that the results achieved by the technique of ultrasound are in agreement with the theoretical equation of Haider and Levenspiel [4], Equation 7.

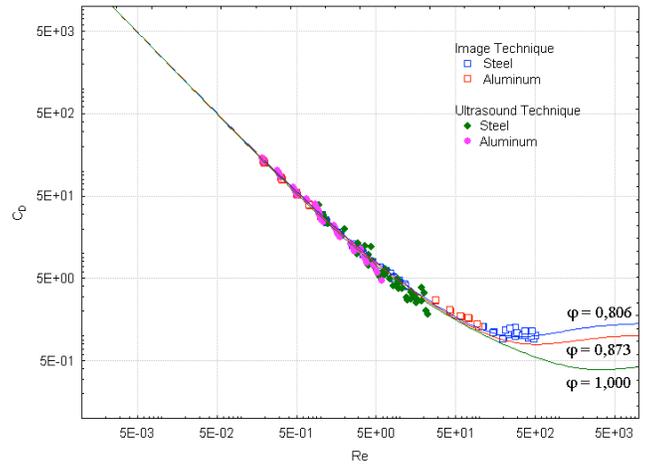


Figure 6. Drag coefficient as a function of Reynolds number for cubes of different sizes and materials.

The same good result to validate the technique of ultrasonic for isometric irregular particles can be observed for the cylinders according to Figure 7.

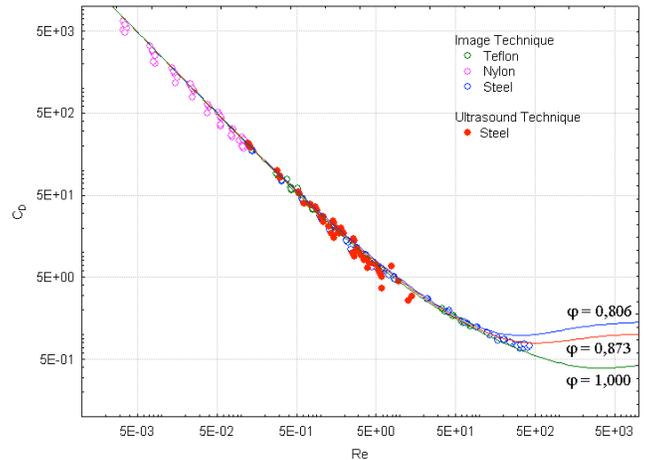


Figure 7. Drag coefficient as a function of Reynolds number for cylinders of dimensions and different materials.

It can be seen that as the particle velocity increases, the experimental results do not match the results obtained from the literature, which shows that the technique is limited to use also for irregular particles.

With relation to the particle sphericity, it is noticed that in low Reynolds number, the drag coefficient correlations show

little dependence on the particle sphericity, the same result observed by Becker [7] in their study, and only with $Re = 500$, approximately, the drag coefficients correlations begin to depend on the sphericity of the particle.

In order to apply the technique of ultrasound in non-Newtonian fluids, some of Carbopol solutions were prepared. The tests were performed by imaging techniques and also by the ultrasound technique. Calculating the appropriate Reynolds number, the results obtained for solutions of spheres Carbopol also showed agreement with the theoretical correlation Haider and Levenspiel (1989), Equation 6, as can be seen by the graph of Figure 8.

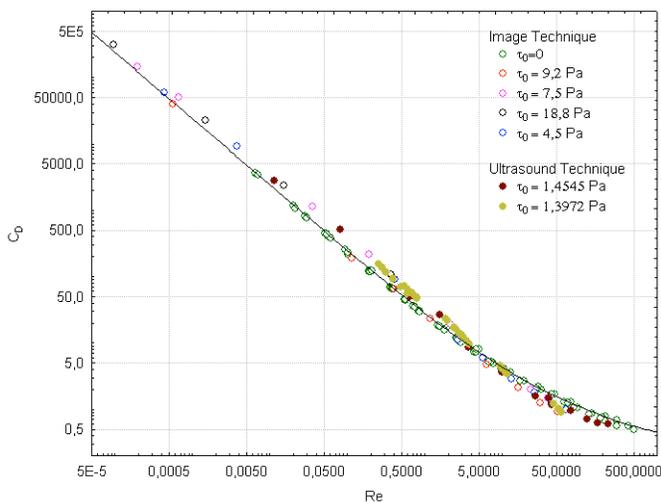


Figure 8. Drag coefficient as a function of Reynolds number for spheres in Carbopol solutions.

Conclusions

The experimental results for regular particles obtained by the technique of ultrasound have a high agreement with the theoretical results obtained in accordance with the correlation of Haider and Levenspiel [4], but the error is influenced by the velocity of the particle. This shows that the technique is limited to use for the configuration performed and that require further investigation to assess wider speed ranges.

Through the results of irregular particles was verified that the results obtained by the technique of ultrasound are also consistent with the literature.

The study of the sedimentation velocity of particles, both regular and irregular, can be further studied by considering some existing effects in non-Newtonian fluids, due to the important application of such fluids in drilling oil wells.

A future proposal would investigate fluids in the presence of fine particulates to observe its influence on the attenuation of ultrasonic signal and the settling velocity of particles.

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