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Modeling of barite sag and fluid flow in drilling fluids

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Abstract: The settling of barite, or any other weighting material, causes undesirable fluctuations in the density of drilling fluids. Problems such as stuck pipe, pressure control difficulties and lost circulation are caused by the settling of barite particles. In this work, we studied a biphasic model to describe the settling and transport of barite particles in oil based drilling fluids. The model is based on the conservation equations and uses the Eulerian approach. The model studied was able to predict the settling and the formation of the particles bed, qualitatively the influence of particle size, liquid viscosity and initial solids concentration. We conducted sedimentation experiments to evaluate parameter of the model. The experimental data were analyzed in terms of the one-way ANOVA test for a 95% confidence level and showed significant reproducibility. The simulation results are qualitatively in accordance with the experimental results.
Keywords: Oil well design; multiphase flow; sag modeling.

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1. Introduction

In oil well drilling, fluids are circulated to clean the wellbore, exert hydrostatic pressure and to stabilize the wellbore walls (Bourgoyne *et al*., 1991). To properly play its functions, the drilling fluid must have controlled physical parameters, such as viscosity and density. To achieve the density needed in some operations, high density solids are added to the drilling fluids. The settling of barite, or any other weighting material, causes undesirable fluctuations in the drilling fluids density. Problems such as stuck pipe, pressure control difficulties and lost circulation are caused by the settling of barite particles (Nguyen *et al.*, 2009).

The mitigation of barite sag is one of the major challenges during the drilling and completion operations (Omland, 2009). Although much has been done, there are no satisfactory solutions, and the phenomenon is still difficult to predict (Nguyen *et al.*, 2009).

In order to simulate the barite sag, we studied a biphasic model, based on conservation equations, to evaluate the solids settling and transport during the flow of drilling fluids. The model was made of partial differential equations and constitutive equations for interaction forces.

We solved the system of partial differential equations by a code developed in Matlab®. The unidirectional settling was studied in order to evaluate the model's sensitivity with respect to the forces and to determine the parameters related to the solid-solid interaction force. The model was discretized by the finite differences approach and the time advancement was made by a BDF integrator.

In order to evaluate experimentally the barite sag, we conducted sedimentation experiments with the graduated cylinder methodology. The experimental results were used to estimate the parameters of a proposed correlation. Simulations data were also compared with experimental results.

2. Material and methods

2.1 Mathematical model

According to Crowe & Michaelides (2006), the dispersed solid-liquid two phase flow can be modeled in different ways: a discrete approach (Lagrangian) or a continuum approach (Eulerian).

Nunziato (1983) used the continuum approach to analyze and solve the flow of fluid with particles. This approach makes two main assumptions: 1. Each phase behaves as a single material, except when it is interacting with the other phase. 2. The equation of motion for the

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mixture takes the same form of the equation for a single phase and it results from summing the equations of motion of each phase of the mixture. According to Nguyen (2009), one advantage of the continuum approach is that it provides the theoretical structure by which models can be extended to high concentrations.

Dong *et al*. (2003 and 2009) studied the formation and growth of the particles cake in sedimentation and filtration processes. These authors used the discrete elements technique (DEM), coupled to computational fluid dynamics (CFD) models. The methodology was effective in predicting the properties of filter cakes and sedimentation. Despite its advantages, the DEM models have high computational cost, which makes unfeasible its application to large systems.

In this work, we used the continuum approach to model the system illustrated in Figure 1, where *L* is the length, *D* is the height, θ is the inclination angle and *g* is the acceleration of gravity. The system was studied in transient conditions in order to evaluate the dynamics of its physics.

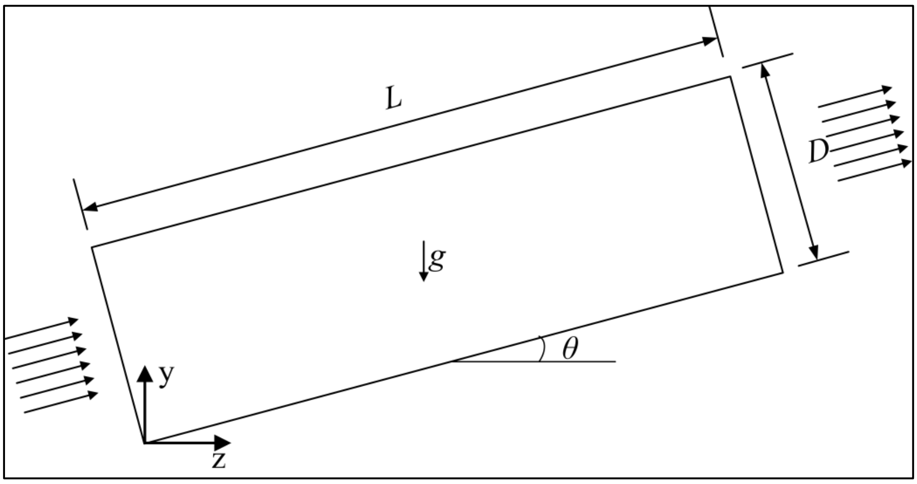

Figure 1. Schematic of the studied system.

The continuity equation for the solid phase is given by:

$$\frac{\partial(c\rho_s)}{\partial t} + \nabla \bullet (c\rho_s v_s) = 0 \tag{1}$$

For the liquid phase, the continuity equation is given by:

$$\frac{\partial((1-c)\rho_l)}{\partial t} + \nabla \bullet ((1-c)\rho_l v_l) = 0 \tag{2}$$

Based on the Eulerian methodology, Shook & Rocco (1991) proposed the following equations for the solid and liquid phase, respectively:

$$\rho_s \frac{d(c\vec{v}_s)}{dt} = -\nabla(cP) + c\rho_s\vec{g} + c\left(\vec{f}_{sl} + \vec{f}_{ss} + \vec{f}_{sw}\right) \tag{1}$$

ISSN: 1415-7314
ISSN online: 2317-6717

$$\rho_l \frac{d\left[(1-c)\vec{v}_l\right]}{dt} = -\nabla\left[(1-c)P\right] + (1-c)\rho_l\vec{g} + (1-c)\left(\vec{f}_{ls} + \vec{f}_{ll} + \vec{f}_{lw}\right) \quad (2)$$

In Equations from **Erro! Fonte de referência não encontrada.** to 2, the subscripts *s*, *l* and *w* refers to solids, liquid and wall, *c* is volumetric concentration of the solid phase, ρ is the density, $\vec{v}$ is the velocity vector, *P* is the pressure and the terms $\vec{f}_{ij}$ refer to the interaction force between *i* and *j* by unit volume. For example, the $\vec{f}_{sl}$ term refers to the interaction force between solids and liquids.

The interaction forces were modeled by well-established literature correlations, such as the Stokes drag law and the Richardson & Zaki's correlation for hindered settling.

In order to simplify the model, we adopted the following considerations: 1. Two dimensional, isothermal and laminar flow; 2. The base fluid is Newtonian; 3.The inclinations angle is equal to zero; 4. The pressure profile in axial direction is linear and constant; 5. The wall effects are neglected.

In this work we proposed three case studies to evaluate the model in simple flow conditions. In the first case study we simulate the two dimensional flow of liquid in the absence of particles, that is, *c*= 0. The second case study involved the simulation of axial flow of fluid and particles, to investigate the presence of slip velocity. The third case study focuses in the unidirectional (no axial flow) particle settling. Further details of the case studies will be given in the discussion section.

The model was solved by a code developed in Matlab®. We used the method of lines to solve the problem: spatial derivatives were discretized by the finite differences approach, and time advancement was made by a BDF integrator.

2.2 Experimental setup

To evaluate the model, we conducted settling experiments using the graduated cylinder methodology. This is a batch sedimentation test in which the fall of the suspension's upper interface is monitored (see Figure 2).

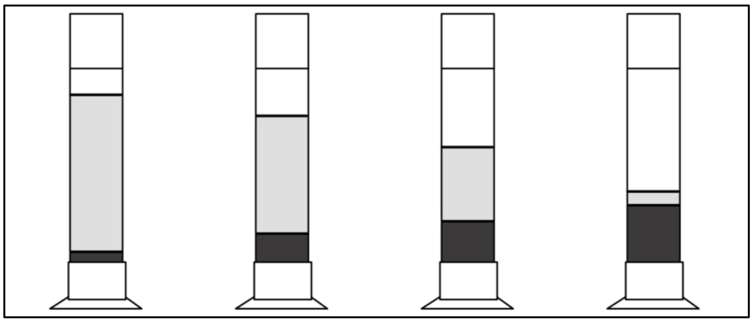

Figure 2. Fall of the upper interface during the batch settling of a suspension.

The tests were conducted with different suspensions of barite in water. We used suspensions of barite in water in order to better scan the interface decay. The suspensions were stirred for 15 minutes in a 1.5 HP mixer and added to a graduated cylinder. Once the suspensions were in the cylinder, the timer was triggered and the fall of the suspension's upper interface was monitored.

The results of the tests were used to evaluate the correlations used in the model. We also compared the experimental results with modeling data. The properties of the suspensions used are presented in Table 1.

Table 1. Suspension's physicochemical properties.

Component	Density (kg.m^{-3})	Viscosity (cP)	Mean Diameter (μm)	Volumetric Fraction (% v/v)
Mineral Oil	850.60	62.00	—	93.30
Barite	4200	—	30.0	6.70

3. Results and discussion

The experimental data were analyzed by the one-way ANOVA, and showed significant reproducibility within a 95% of confidence interval.

3.1 Two dimensional flow of liquid in the absence of particles

In this case study, Equations **Erro! Fonte de referência não encontrada.** and 2 were used for c= 0. Writing the equations in scalar form, the model reduces to:

$$\frac{\partial v_{ly}}{\partial y}+\frac{\partial v_{lz}}{\partial z}=0, \tag{3}$$

$$\frac{\partial v_{lz}}{\partial t}=\frac{1}{\rho_l}\left(-\frac{\partial P}{\partial z}+\mu_l\left[\frac{\partial^2 v_{lz}}{\partial y^2}+\frac{\partial^2 v_{lz}}{\partial z^2}\right]\right)-v_{ly}\frac{\partial v_{lz}}{\partial y}+v_{lz}\frac{\partial v_{lz}}{\partial z}, \tag{4}$$

ISSN: 1415-7314
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$$\frac{\partial v_{ly}}{\partial t} = \frac{1}{\rho_l}\left(-\frac{\partial P}{\partial y} + \mu_l \left[\frac{\partial^2 v_{ly}}{\partial y^2} + \frac{\partial^2 v_{ly}}{\partial z^2} \right] + \rho_l g \right) - v_{ly}\frac{\partial v_{ly}}{\partial y} + v_{lz}\frac{\partial v_{ly}}{\partial z} \cdot \quad (5)$$

The initial and boundary conditions used for this case were:

$$y = 0 \qquad \vec{v} = 0 \qquad \forall t , \quad (6)$$

$$y = D \qquad \vec{v} = 0 \qquad \forall t , \quad (7)$$

$$z = 0 \qquad v_{lz} = v_{z0} \qquad \forall t , \quad (8)$$

$$z = 0 \qquad v_{ly} = 0 \qquad \forall t , \quad (9)$$

$$z = L \qquad \frac{\partial \vec{v}}{\partial z} = 0 \qquad \forall t , \quad (10)$$

$$t = 0 \qquad v_{lz} = v_{z0} \qquad \forall z;\ y \neq 0;\ y \neq D , \quad (11)$$

$$t = 0 \qquad v_{lz} = v_{z0} \qquad \forall z;\ \forall y . \quad (12)$$

The input data used in this simulation are presented in Table 2.

Table 2. Parameters used in the first case study.

Variable	**Symbol**	**Value**	**Units**
Height	D	0.1016	m
Length	L	10.67	m
Gravity	G	9.81	$m.s^{-2}$
Pressure drop z	ΔP_z	200.00	Pa
Pressure drop y	ΔP_y	$\rho \cdot g$	Pa
Initial velocity	v_{z0}	0.1557	$m.s^{-1}$

The results for the simulation of 30 seconds of flow are presented in Figure 3. The fluid used was a mineral oil (μ=62 cP and ρ=850.6 $kg.m^{-3}$). In this case, one can observe the formation of the parabolic velocity profile, which is the classic solution for this flow configuration. Near the entrance, one can observe the plug flow behavior, which was the feed condition used in this simulation.

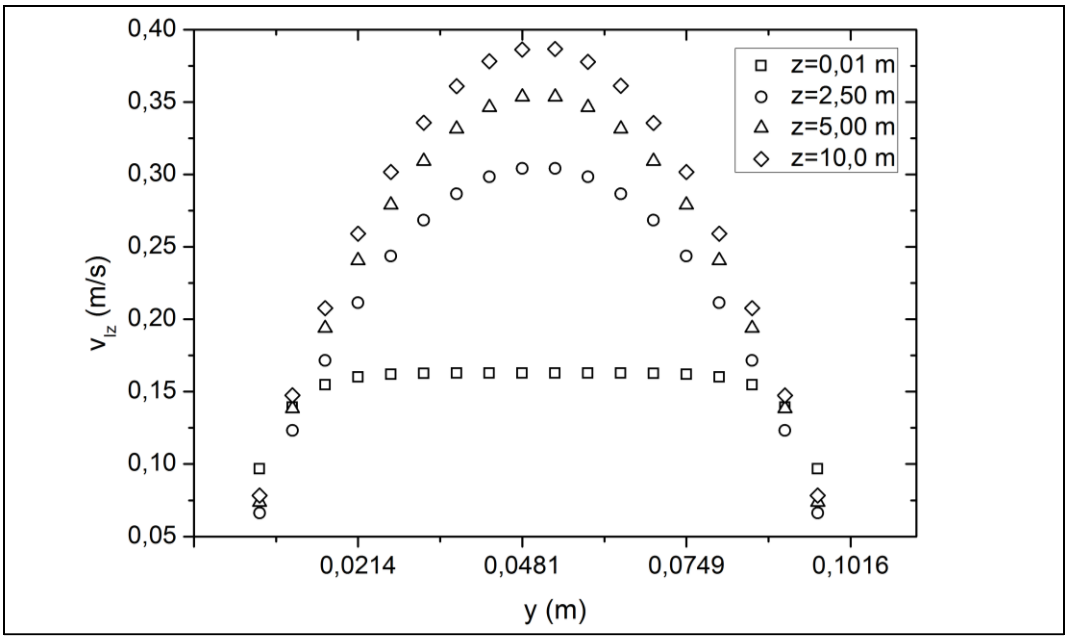


Figure 3. Velocity profile as a function of the height (y) for different positions (z).

The results for z=10m were compared with the classic parabolic profile, given by (Bird *et al*., 2006):

$$v_{lz\infty} = \frac{\Delta P}{2\mu L}\left(y^2 - Dy\right). \quad (13)$$

The comparison of the velocity profile for z=10m and t=30s is presented in Figure 4.

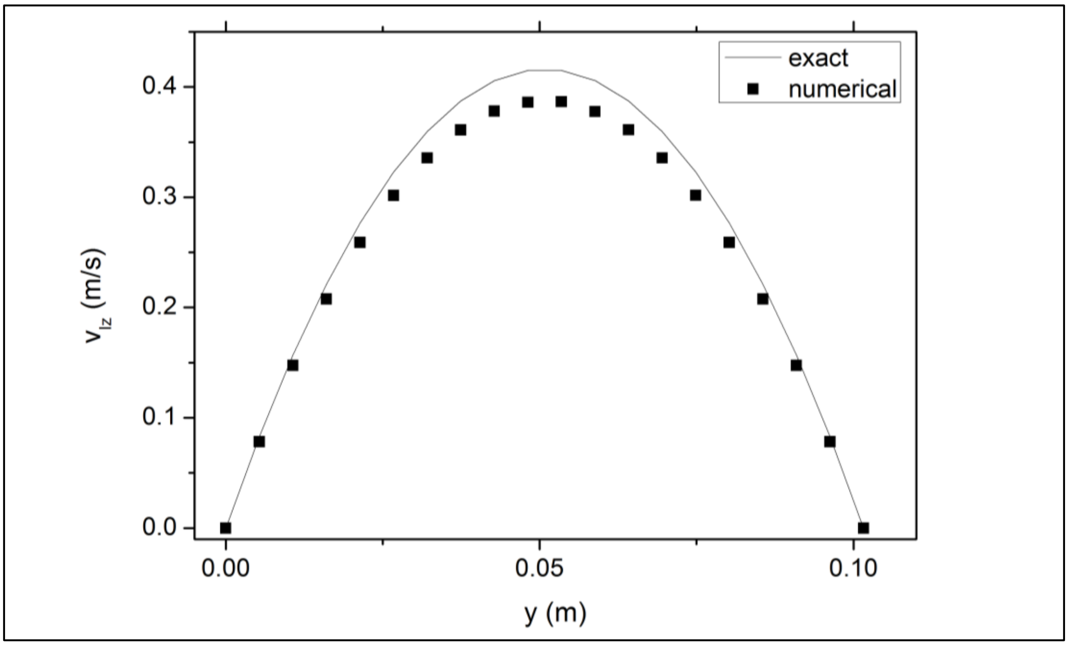


Figure 4. Velocity profile as a function of y. — exact solution, ■ numerical results.

The model is quantitatively in accord to the exact solution and the deviations were less than 7%.

3.2 Axial flow of fluid and particles

In this case study the z-component of Equations 1 and 2 were used, the mode reduces to:

$$\frac{\partial v_{sz}}{\partial t} = -\frac{1}{\rho_s c}\left(c\frac{\partial P}{\partial z} + P\frac{\partial c}{\partial z} \right) + \frac{1}{\rho_s}\left(f_{sl}^{z} + f_{ss}^{z} \right), \tag{14}$$

$$\frac{\partial v_{lz}}{\partial t} = -\frac{1}{\rho_l (1-c)}\left[(1-c)\frac{\partial P}{\partial z} - P\frac{\partial c}{\partial z} \right] + \frac{1}{\rho_l}\left(f_{ls}^{z} + f_{ll}^{z} \right). \tag{15}$$

To model the interaction force between solids and liquid, Equation 18 was used.

$$f_{sl}^{z} = \frac{3C_{Dz}\rho_l \left(v_{l,z} - v_{s,z} \right)}{4d_s (1-c)^{1.7}} \left| v_{l,z} - v_{s,z} \right|, \tag{16}$$

where

$$C_D = \frac{24}{\mathrm{Re}_{sz}}, \tag{17}$$

and

$$\mathrm{Re}_{sz} = \frac{d(1-c)\left| v_{l,z} - v_{s,z} \right| \rho_l}{\mu_l}. \tag{18}$$

To quantify the liquid-solid force, the continuum approach was used. Once this methodology considers that all momentum lost by a phase is gained by the other phase, Equation 21 was used to this calculation.

$$c f_{sl}^{z} + (1-c) f_{ls}^{z} = 0 \qquad or \qquad f_{ls}^{z} = -\frac{c}{(1-c)} f_{sl}^{z} \tag{19}$$

The solid-solid and liquid-liquid forces were modeled in a similar way using the shear force (see Equations **Erro! Fonte de referência não encontrada.** and **Erro! Fonte de referência não encontrada.**, respectively).

$$c f_{ss}^{z} = -\mu_s \nabla \bullet \left(c\frac{\partial v_{s,z}}{\partial y} \right) = -\mu_s \frac{\partial}{\partial y}\left(c\frac{\partial v_{s,z}}{\partial y} \right) \tag{22}$$

$$(1-c) f_{ll}^{z} = -\mu_l \nabla \bullet \left[(1-c)\frac{\partial v_{l,z}}{\partial y} \right] = -\mu_l \frac{\partial}{\partial y}\left[(1-c)\frac{\partial v_{l,z}}{\partial y} \right] \tag{23}$$

The initial and boundary conditions used for this case were:

$$y = 0 \qquad v_{lz} = v_{sz} = 0 \qquad \forall t, \tag{20}$$

$$y = D \qquad v_{lz} = v_{sz} = 0 \qquad \forall t, \tag{21}$$

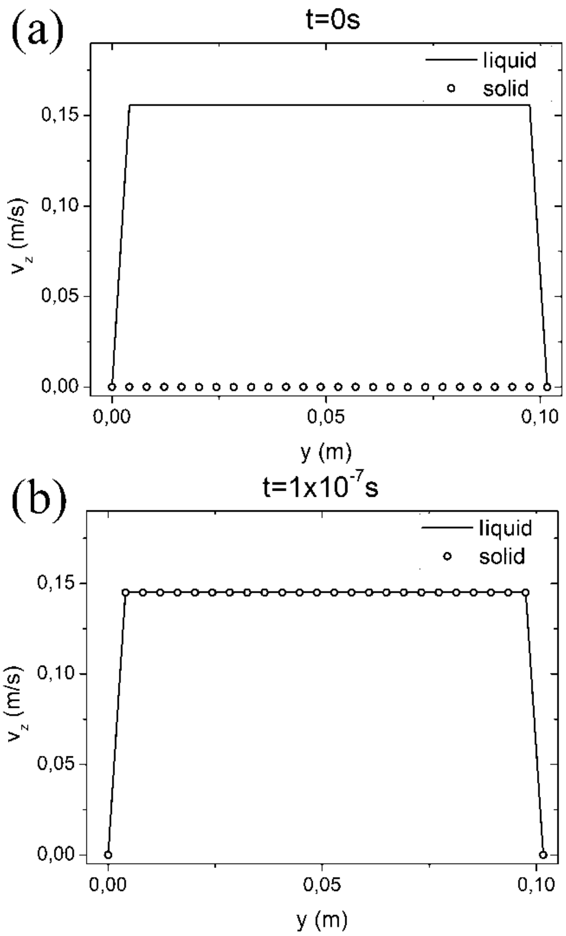
$$t = 0 \qquad v_{lz} = v_{z0} \qquad y \neq 0; y \neq D, \tag{22}$$

$$t = 0 \qquad v_{sz} = 0 \qquad y \neq 0; y \neq D. \tag{23}$$

In this case, one can notice that in the simulation start, solids had velocity equals to zero. This was assumed to analyze the necessary time for the solids reach 99% of the liquid velocity and to verify the existence or not of the slip velocity.

In

Figure 5, the results for this case study are presented. The simulation was carried (out) for suspensions of 6.7 % v/v of barite particles (ρ= 4200 kg.m^{-3} and d_s= 25μm) in mineral oil (μ= 62 cP and ρ= 856.6 kg.m^{-3}). The observed slip velocity was of the order of $1 \cdot 10^{-8}$ m/s, and the necessary time for the solid particles reach 99% of the liquid velocity was of the order of $1 \cdot 10^{-7}$ s. This is an indication that we can use an equation for z average speed, which will spend less computational resources.



ISSN: 1415-7314
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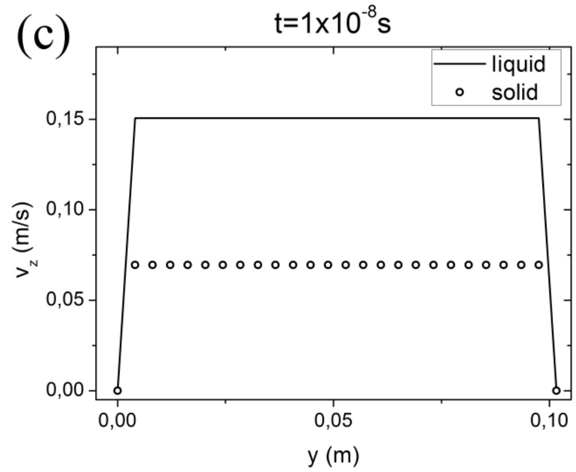


Figure 5. Velocity profile of liquid and solids flow at different times. (a) t = 0 s; (b) t = $1{\cdot}10^{-7}$ s; (c) t = $1{\cdot}10^{-8}$ s.

3.3 Unidirectional (no axial flow) particle settling

This case study uses the model to simulate the batch sedimentation process. Particles settle down vertically, without axial flow, as shown in Figure 2. In this case study, the Equation **Erro! Fonte de referência não encontrada.** and the y-component of Equations 1 and 2 were used, the mode reduces to:

$$\frac{\partial c}{\partial t} = -c\frac{\partial v_{sy}}{\partial y} - v_{sy}\frac{\partial c}{\partial y}, \tag{24}$$

$$\frac{\partial v_{sy}}{\partial t} = -\frac{1}{\rho_s c}\left(c\frac{\partial P}{\partial y} + P\frac{\partial c}{\partial y}\right) - g + \frac{1}{\rho_s}\left(f_{sl}^{y} + f_{ss}^{y}\right), \tag{25}$$

$$\frac{\partial v_{ly}}{\partial t} = -\frac{1}{\rho_l\left(1-c\right)}\left[\left(1-c\right)\frac{\partial P}{\partial y} - P\frac{\partial c}{\partial y}\right] - g + \frac{1}{\rho_L}\left(f_{ls}^{y} + f_{ll}^{y}\right). \tag{26}$$

The forces modeling were made in the same way of the previous case study (see Equations 16-**Erro! Fonte de referência não encontrada.**), with exception of the interaction force between solids in the y direction. Instead of using the shear force, we assumed a quadratic form correlation, as shown in Equation 31.

$$f_{ss}^{y} = p\left(c\right)^{2} \tag{27}$$

The initial and boundary conditions used for this case were:

$$y = 0 \qquad v_{ly} = v_{sy} = 0 \qquad \forall t, \tag{28}$$

$$y = D \qquad v_{ly} = 0 \qquad \forall t, \tag{29}$$

$$t = 0 \qquad v_{ly} = v_{sy} = 0 \qquad \forall y, \tag{30}$$

ISSN: 1415-7314
ISSN online: 2317-6717

$$t = 0 \qquad c = c_0 \qquad \forall y. \tag{31}$$

The parameter *p* was determined from experimental data, presented in Figure 6. These are results for a triplicate of tests for the sedimentation of barite particles in water (μ=1 cP and ρ=1000 kg.m^{-3}). The parameter assumes a value that stops the settling when a critical solids concentration is reached. For this case, the value of the parameter is 61.

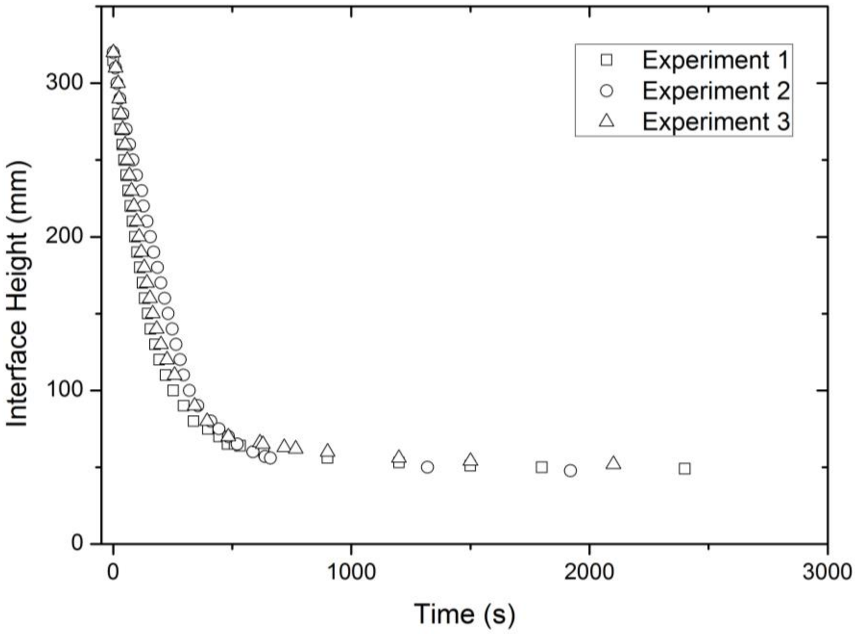
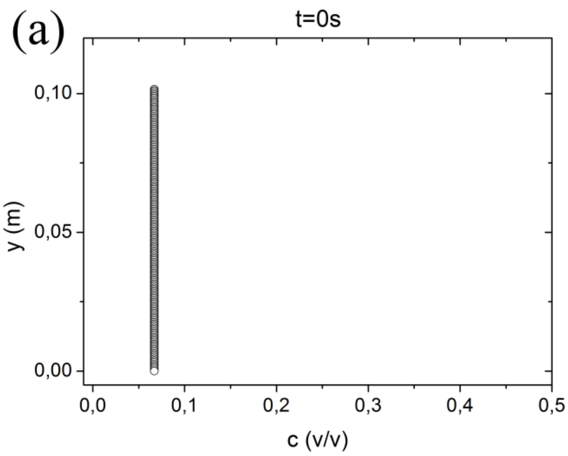


Figure 6. Height of interface versus time (c = 6%v/v).

Concentration profiles as a function of height for the simulation of barite particles in water are presented in Figure 7. In these profiles, one can observe the fall of the top of the suspension and the formation of a particle bed in the bottom of the system.



ISSN: 1415-7314
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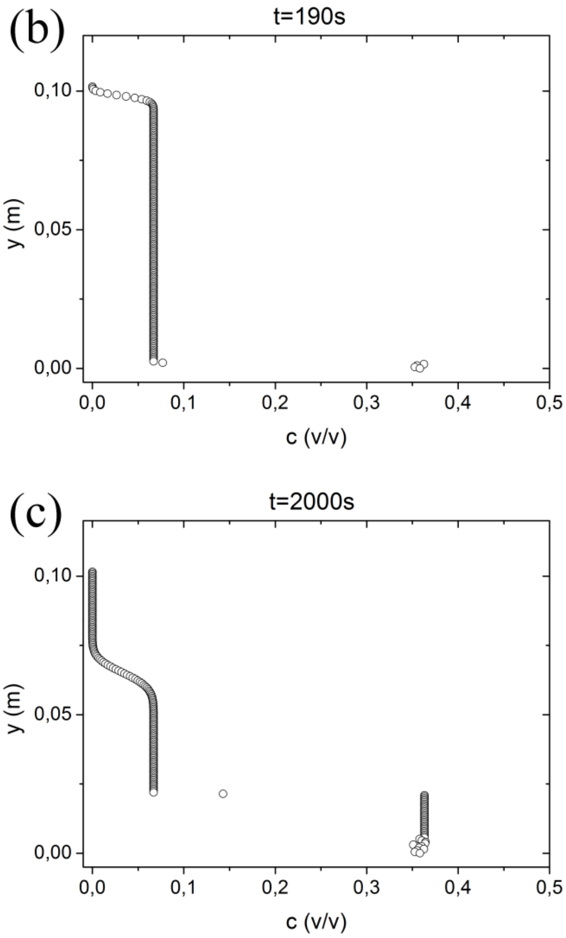

Figure 7. Concentration profile as a function of height for $c_0 = 6.7\%$.

The fall of the suspension's upper interface calculated by the model and experimentally observed is presented in Figure 8.

ISSN: 1415-7314
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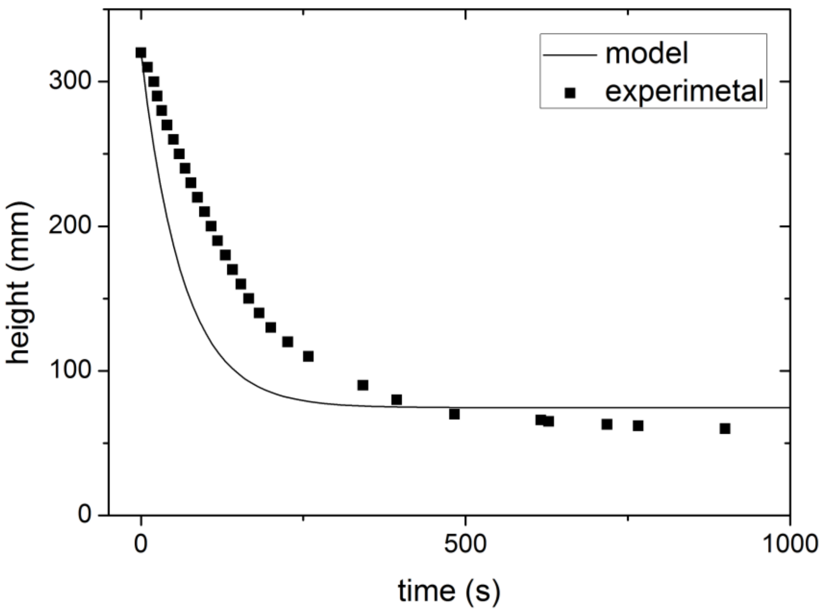

Figure 8. Suspension's upper interface height as a function of time.

The model predicts the presence of three distinct zones: a clarified liquid zone, the settling zone and the particles bed zone. No compression zone was observed, because we did not use correlations to predict the compression phenomenon. The model predicts qualitatively the experimental results of suspension's upper interface fall.

The influence of particle size, liquid viscosity and initial solid concentration were also evaluated. We used 3 particle sizes, 3 liquid viscosities and 3 initial solid concentrations to evaluate its influence in the model behavior.

Simulations were carried out with particles of 10, 30 and 60 micron. The viscosity used in these simulations was 1cP and the initial solid concentration was 6%. The results for these 3 simulations are present in Figure 9. One can observe that with particle size increase, the settling speed increases too. It is known that, as particle diameter approaches to zero, the system tends to behave like a single phase (Brennen, 2005).

Simulations were carried out with fluid viscosities of 1, 3 and 5 cP. The particle diameter used in these simulations was 30 micron and the initial solid concentration was 6%. In Figure 10, the results for simulations with these 3 different viscosities are presented. One can observe that with viscosity increase, the settling speed decreases. That happens because of the higher drag force in more viscous liquids.

ISSN: 1415-7314
ISSN online: 2317-6717

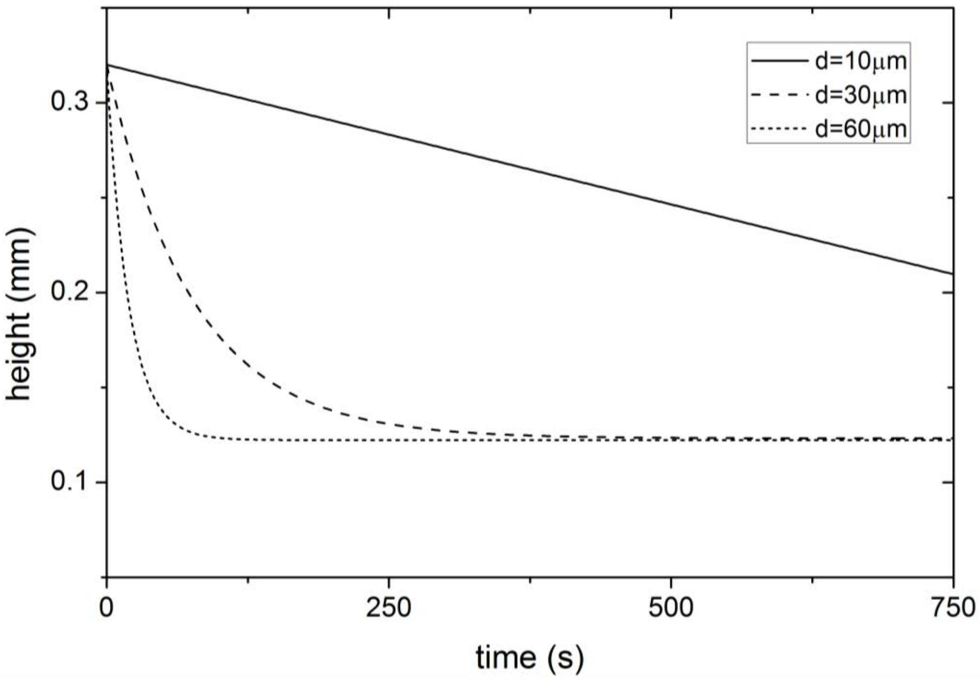

Figure 9. Suspension’s upper interface height as a function of time.

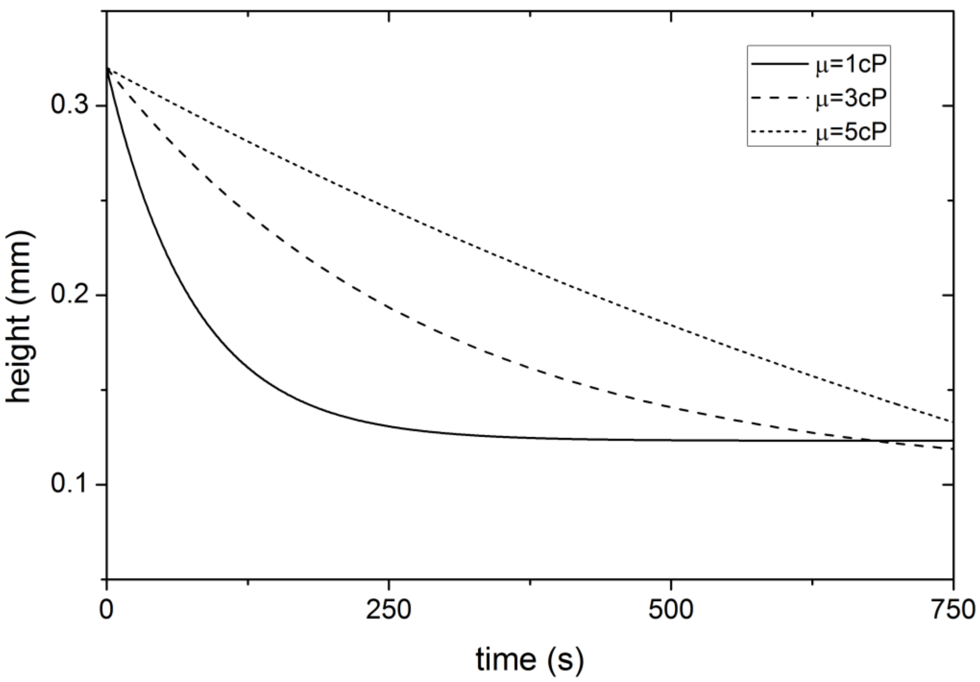

Figure 10. Suspension’s upper interface height as a function of time.

Simulations were carried with initial concentrations of 6, 12 and 20%. The viscosity used in these simulations was 1cP and particle diameter was 30 micron. In Figure 11, the results for 3 initial solids concentration are presented. One can observe that with solids concentration increase, the settling speed decreases. That is the physical behavior observed experimentally and well-posed in literature, which is known as hindered settling (Massarani, 2002).

ISSN: 1415-7314
ISSN online: 2317-6717

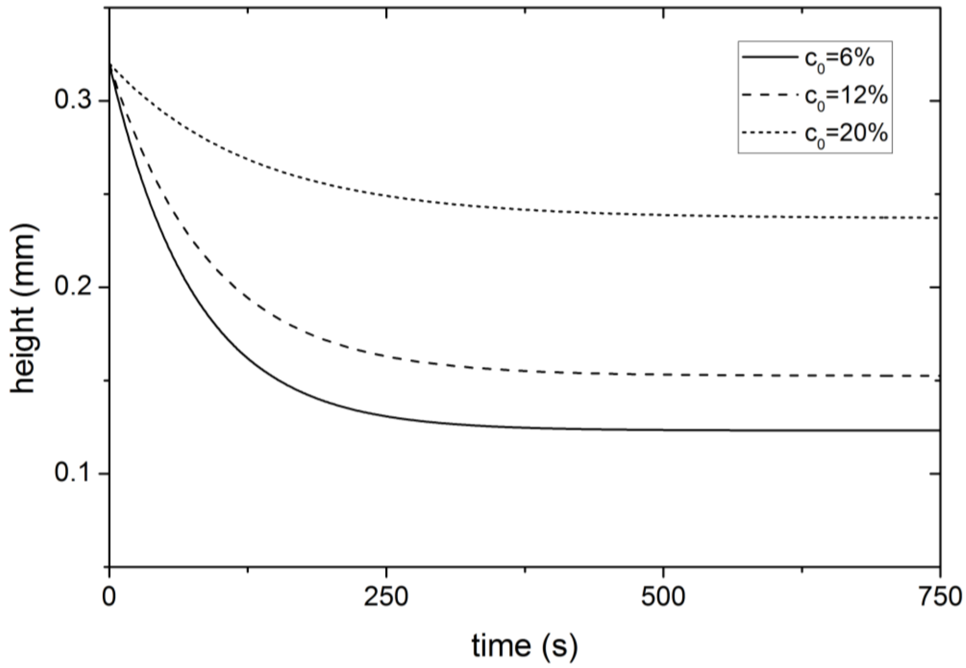

Figure 11. Suspension's upper interface height as a function of time.

4. Conclusions

We studied a model to evaluate the barite sag in oil based drilling fluids. A classical set of equations proposed by Shook & Rocco (1991) was used in three case studies with success. The set of equations was able to predict the two dimensional fluid flow, the particle drag by a fluid and the batch settling process. The model is in accord to classical analytical solutions and to experimental data.

Simulations were carried out to evaluate the model behavior in different settling conditions. We carry out simulations with 3 particles sizes ranging from 10 to 60 micron. The model predicts that increases in particle diameter increases the settling rate. Simulations were carried with 3 viscosities and with 3 initial solids concentrations. We evaluated viscosities from 1 to 5 cP and initial solids concentrations from 6 to 20%. The model was able to predict that an increase in liquid viscosity slows down the settling. The model was also able to predict that an increase in initial solids concentration reduces the settling rate, which is known as hindered settling.

The forthcoming step is to evaluate the model in cases studies involving all phenomena that was studied separately in this work. The full model validation will be performed with experimental and field data.

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6. Nomenclature

c	Solids volumetric concentration
C_D	Drag coefficient
D	Diameter of the simulated system
d_s	Particle diameter
f	Force per unit of volume
g	Acceleration of gravity
l	Index to refer to the liquid phase
L	Length of the simulated system
p	Force parameter
P	Pressure
Re	Reynolds number
s	Index to refer to the solid phase
v	Velocity
w	Index to refer to the walls

Greek letters

θ	Inclination angle
μ	Viscosity
ρ	Density

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