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SOLIDS TRANSPORT IN LAMINAR FLOW

Tálita Coffler Botti
Márcio da Silveira Carvalho
Department of Mechanical Engineering
Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio)
Rua Marquês de São Vicente, 225, Gávea - Rio de Janeiro, RJ – Brasil.
Cep: 22451-900.
talita.c.b@hotmail.com; msc@puc-rio.br

Abstract. *After the 80's, the use of directional wells became frequent in the development of oil fields, allowing great progress in exploration. This scenario, however, brings great challenges to operations related to wellbore cleaning, that consists in the removal of cuttings from within the annular through the circulation of drilling fluid. Due to the inclination of the well, the cuttings undergo the action of gravity, migrating to the bottom of the channel, as they have higher density than the liquid phase and they may be transported with a speed less than the speed of the liquid flow. Then the cuttings form a stationary bed, blocking part of the annular and decreasing the flow rate that causes problems, such as reducing the rate of penetration, high torque and drag, trapping column and others. This research studies the laminar two-dimensional flow of solid particles suspended in a liquid due to a pressure gradient between two parallel plates, representing a simplified description of the flow that occurs in an annular during the drilling process. The profile of the particle bed along the channel and the flow rate pressure difference relationship for different flow conditions are determined. The mathematical formulation leads to a coupled system of three differential equations: mass and momentum conservation and transport equation, which includes the effects of particle diffusion due to the frequency of interaction between the particles, the gradient of viscosity and the difference density between the liquid and the particles. The system is solved by the finite element method Galerkin.*

Keywords: *Particle transport; viscous resuspension; finite element method; drilling.*

1. INTRODUCTION

During the oil well drilling operation sediments are generated, which are removed from the well annulus by the flow of drilling mud. Usually, hole cleaning is accomplished by circulating the drilling fluid through the drillstring and out the jets of the bit reaching the annular gap space formed between the column and the well wall, where are the cuttings.

Removing these cuttings is not always carried out successfully and the process is strongly influenced by system geometry, for example, in horizontal wells or large slope. In such cases, gravity may lead to formation of a bed of particles, since the solids tend to settle more easily in the bottom of the channel (Fig. 1). This may cause a series of problems, such as: reduced penetration rate, loss circulation, high torque and drag, annular obstruction, column prison and may even cause the loss of the well (Costa and Fontoura, 2005).

Directional wells became frequent in the operations of oil fields development in the 80 and 90. Today, the vast majority of development wells is directional, including horizontal and long-range wells. The advancement of this technology allowed these wells to reach goals increasingly distant from the target, and are used as productivity-enhancing method, since it exposes a greater extent the reservoir to production.

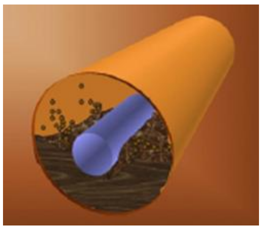

Figure 1 - Annular with cuttings bed (Source: Costa and Fontoura, 2005)

As the operating costs of drilling, both an exploratory well as a development well, are high, it is necessary to study the problems that occur in order to minimize them, searching for more accurate models to describe the different processes.

The problem of solid transport does not occur only in the scenario of the oil industry. The focus of this study is the viscous resuspension phenomenon, first observed by Gadala-Maria (1979), followed by several authors. This phenomenon is the process whereby, in the presence of a shear flow, a layer of hard particles denser than the surrounding liquid, initially at rest, is again put in motion, being entrained by the fluid, even in very small Reynolds conditions.

Leighton and Acrivos (1986) pointed out that this phenomenon was first observed by Gadala-Maria in 1979, when they measured the rheological properties of carbon particles suspended in a Newtonian fluid using a parallel plate device. Noting that, when the suspension was sheared at low shear rates after having been at rest, the initial value of the viscosity was significantly lower than that measured previously at rest. A part of the particles had been deposited, forming a bed which subsequently sheared again as it would have been resuspended causing the viscosity to reach the same initial value. Then Leighton and Acrivos repeated this experiments and explained this phenomenon in terms of the diffusion process induced by shear, unlike conventional Brownian diffusion (overlooked due to the size of the particles used).

Schaflinger et al. (1990) theoretically investigated the viscous resuspending for two different cases, the two-dimensional Hagen-Poiseuille flow and the gravity flow film along an inclined plane. In both cases, the shear stress isn't constant. For the Hagen-Poiseuille flow there is a plane in the channel where it is equal to zero, imposing an upper limit on the height of the resuspended layer. Furthermore, for the flow of the film under the action of gravity, a critical value is determined for the solids volumetric concentration in the feed, above which the particles settle and form a sediment layer on the plate that grows continuously as a function of time. This study considers that the flow of descending particles due to gravity is balanced by the diffusive flux caused by the random motion of particles by induced shear.

Phillips et al. (1992) proposed a mathematical formulation to describe the particle concentration and velocity fields in concentrated monomodal suspensions, consisting of: a Newtonian constitutive equation in which the viscosity depends on the local particle volume fraction and a diffusion equation that accounts for shear-induced particle migration, called *diffusion flow model*. In this type of flow, it is observed particle migration from regions with high to low shear rates.

Zhang and Acrivos (1994) studied the viscous resuspension of heavy particles in a fully developed laminar flow in a horizontal pipe through the extended Phillips' model for cases in which all three components of the velocity are nonzero due to the existence of second-motion in the cross section of the pipe. They have applied the finite element method to solve the system of differential equations.

Most theoretical work in the literature consider the flow to be developed. The aim of the present analysis is to determine the bed height and the relationship flow-pressure difference depending on the conditions of flow and properties of the fluid and the solid particles. The formation and growth of the particle bed is generally not investigated because of the complexity of the problem increases considerably.

The flow of suspensions of solid particles due to a pressure gradient between two parallel plates is analyzed here. It is a simplified description of the flow that occurs in annular during the drilling process. The study will allow the determination of the particle bed profile, i.e. the variation in height along the bed of the channel; and the flow-pressure difference relative to different flow conditions: flow or imposed pressure differential and density difference between solids and the liquid phase.

2. MATHEMATICAL FORMULATION

The particle suspension is considered as a continuous medium. The flow is assumed to be laminar and governed by the mass and momentum conservation equations and an equation to describe the particles transport in the liquid medium, the convection-diffusion equation, which describes the concentration distribution of these particles. We analyze the steady state solution.

In the oil industry scenario, solid suspension flow in an annular well is a complex problem because it involves a three-dimensional geometry in cylindrical coordinates and the complex fluid flow. To simplify the problem, we consider a two-dimensional flow between parallel plates. Despite the geometric difference, this flow presents all important physical phenomena of the flow in an annular. The problem studied, shown in Fig. 2, is the flow due to a pressure difference between two parallel plates. It is considered that the inflow particles concentration is uniform and the velocity profile, parabolic. The channel has length L and height H.

The goal is calculating the pressure, velocity and concentration fields in the flow domain, and to determine the height of the bed deposited on the bottom of the channel as a function the problem variables.

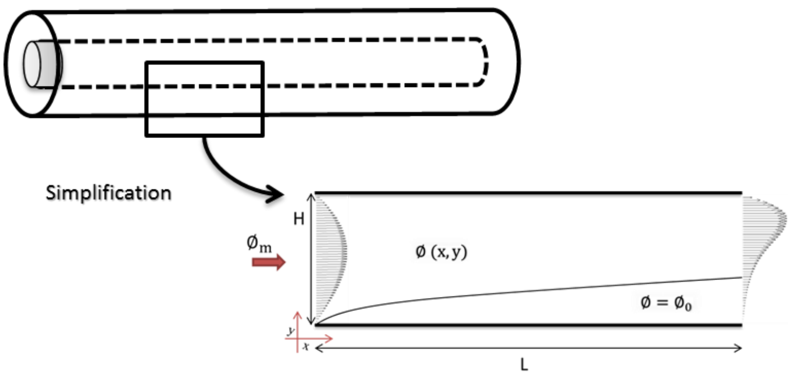

Figure 2 - Scheme that represents a simplification of the geometry of the problem.

In the inflow plane (Fig. 2) the particle concentration is uniform, $\varnothing_m$. Two distinct regions are formed in the flow: one at the base of the channel, with more particle deposition, that will increase both the suspension viscosity, in this region the speed approaches zero, i.e. stagnant bed; other region following to the top of the channel, where the particles are carried by the fluid. Depending on conditions, it is observed on the top of the channel, a clean fluid region.

Some hypotheses are adopted to simplify the problem: flow in steady state; incompressible liquid phase; two-dimensional flow; negligible inertia effects. As Leighton and Acrivos (1986), we also disregard the effect of Brownian diffusion, since the particle size is considered large enough ($d > 1\mu m$).

2.1 Governing Equations

The equations are derived from the principles of mass and momentum conservation (Panton, 2005). The suspension is considered as a continuous incompressible medium.

$$\nabla . \vec{v} = 0 \,, \tag{1}$$

$$\nabla . \bar{\bar{T}} = 0 \,. \tag{2}$$

The stress tensor $\bar{\bar{T}}$ may be decomposed in terms of pressure and a viscous stress tensor: $\bar{\bar{T}} = -p\bar{\bar{I}} + \bar{\bar{\tau}}$, where $\bar{\bar{I}}$ is the identity tensor and $\bar{\bar{\tau}}$ is represented by:

$$\bar{\bar{\tau}} = \mu(\emptyset)\bar{\bar{\dot{\gamma}}} \,, \tag{3}$$

where $\bar{\bar{\dot{\gamma}}}$ is the strain rate tensor given by: $\bar{\bar{\dot{\gamma}}} = \nabla\vec{v} + \nabla\vec{v}^T$. $\mu(\emptyset)$ is the viscosity of the suspension, which is a function of the local particle concentration. The model used to describe the effective viscosity used was the one proposed by Krieger (1972),

$$\mu_r = {\mu(\emptyset)}/{\mu_l} = \left(1 - \frac{\emptyset}{\emptyset_0}\right)^{-2.67\emptyset_0} , \tag{4}$$

μ_r is the suspension relative viscosity, μ_l is the liquid viscosity and $\emptyset_0$ is the maximum packing volume fraction, equal to 0.68 in our study.

These models that take into account the maximum packing fraction possess a singularity point when this value is reached, Fig. 3. The value of $\emptyset_0$ depends of the form and of particles interaction. To monodispersed spheres its value is between 0.58 and 0.72. It is possible note from the graph that at concentrations higher than 0.5 the suspension viscosity begins to rise taking rapidly this value to infinity.

And the last equation that composes this system is the particles transport equation, based on mass conservation of solid particles, given by:

$$\vec{v} . \nabla\emptyset = \nabla . N_t . \tag{5}$$

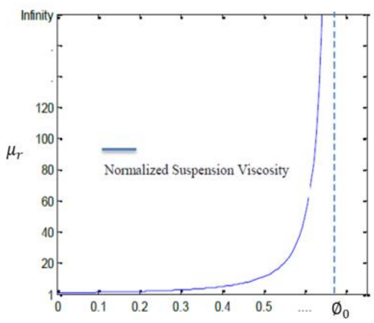

Figure 3 – Suspension viscosity normalized (Source: Silva, 2013).

N_t represents the total flow of particles due to different particle migration mechanisms.

Phillips et al. (1992) points out that interactions between two spherical and smooth particles suspended in a flow are reversible, so each particle can return to its original plate after the collision. However, if this migration occurs from high shear to low shear regions there will be an irreversible interaction component that does not allow the particles to return to their original streamlines.

In this work, we assume that the particles migration occurs through three mechanisms:

a) **Shear rate gradient mechanism migration:** This mechanism is associated to the frequency of collisions between the particles. The particles collide due the relative speed difference of the adjacent streamlines. The frequency of collisions is proportional to the shear rate, which results in higher frequency of collisions between particles in regions with higher shear rates. Thus, the particle migration is the movement of high to low shear regions, as illustrated in Fig. 4(a). The constitutive equation that describes this flux used was proposed by Phillips et al (1992) as follows, where a is the particle radius and K_c is a proportionality constant set by experimental data:

$$\mathrm{N_c} = -\mathrm{K_c}\mathrm{a}^2(\emptyset^2\nabla\dot{\gamma} + \emptyset\dot{\gamma}\nabla\emptyset). \tag{6}$$

b) **Viscosity gradient migration mechanism:** occurs because of the resistance to movement of a particle in regions with high viscosity. In Fig. 4(b) there is a flow with constant viscosity field where after the collision of two particles moving in the same way, to experience the same resistance to motion. In the Fig. 4(c), the viscosity field is variable, so it is observed that there is a greater displacement of particles in the low viscosity region, unlike what happens in the upper regions viscosity because they retard the particles movement. The constitutive equation used was proposed by Phillips et al (1992) and their representation is the follows, where K_μ is a constant of proportionality established experimentally:

$$N_\mu = -K_\mu \dot{\gamma} \emptyset \left(\frac{a^2}{\mu}\right) \frac{d\mu}{d\emptyset} \nabla \emptyset. \tag{7}$$

c) **Sedimentation mechanism:** because of the density difference between the liquid and the particles, represented by Leighton and Acrivos (1986) as follows:

$$N_g = \frac{2}{9} \emptyset f(\emptyset) \frac{a^2 \Delta\rho}{\mu_l} \vec{g}\,, \tag{8}$$

where μ_l is the liquid viscosity, $\Delta\rho$ is the difference between the liquid and solid phases density, $f(\emptyset)$ is a function that takes into account the presence of other particles in the suspension by decreasing the particles flow to high concentration regions. For simplicity Schaflinger et al (1990) adopted the corresponding function obtained in experiments vertical, represented by:

$$f(\emptyset) = \frac{1-\emptyset}{\mu_r}. \tag{9}$$

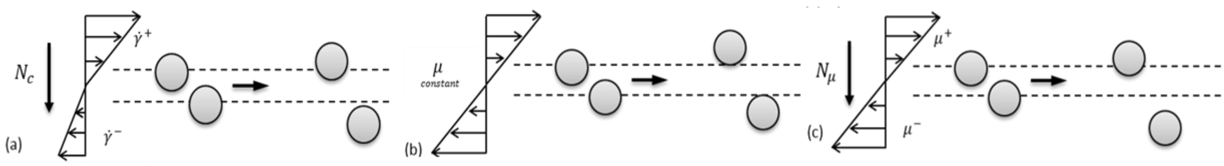

Figure 4 – Irreversible collision between two bodies with (a) variable shear rate, (b) constant viscosity, and (c) spatial variation of viscosity (Source: Phillips et al. 1992).

The dimensionless parameters describing the flow are:

Hydrodynamic Peclet number (*Pe*): ratio between the convective - diffusion transport of suspended particles.	$Pe = \frac{V.H}{K_c.a^2.V/H} = \frac{H^2}{K_c.a^2}$
Diffusivities ratio (λ):	$\lambda = \frac{K_c}{K_\mu}$
Sedimentation number (s): ratio between the sedimentation and convective flows.	$s = \frac{2}{9}\frac{a^2.g.\Delta\rho.L}{H^2.\Delta P}$
Dimensionless Pressure differential:	$\Delta P^* = \frac{H}{\mu_l}\sqrt{\rho_l.\Delta P}$
Dimensionless flow, where $\bar{\mu}$ is the viscosity of the suspension to the average particle concentration.	$Q^* = \frac{Q}{Q_m} = \frac{Q}{\frac{H^3}{12.\bar{\mu}}.\frac{\Delta P}{L}}$

Through the literature (Li, 2007), it was possible to estimate some values of these parameters in the real case, as shown in Tab. 1. Note that some values are slightly different because to the numerical limitation of program that did not allow to simulate for large well lengths.

Table 1 - Comparing the values of some dimensionless for the real case and this paper.

	Real case	**Present work**
λ	$0.1 \leq \lambda < 1$	$0.1 \leq \lambda < 1$
ΔP^*	~ 8000	< 3000
Pe	$10^2 - 10^5$	$10^3 - 10^5$
s	$\sim 10^{-9}$	$10^{-5} - 10^{-4}$
Q*	$0.4 - 1.0$	$0.03 - 1.2$

2.2 Boundary Conditions

Figure 5 presents the flow domain and the boundary conditions used. At the entrance the velocity profile is assumed to be fully developed, the inlet pressure is imposed (P_1) and the concentration profile is constant $(\emptyset_m)$. Along the walls, no-slip, no-penetration and no particle flux conditions are applied. And the outlet, the pressure is set to $P_2 = 0$.

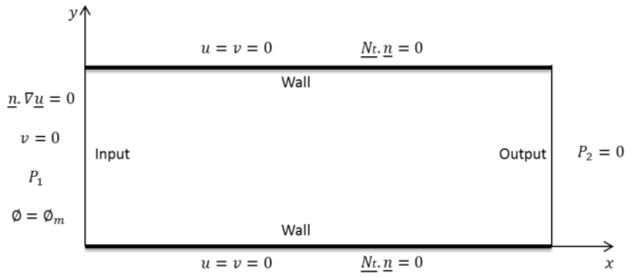

Figure 5 - Boundary conditions used in the problem.

2.3 Solution Method

The differential equations system is solved by the Finite Element Method with quadrilateral finites elements. To present the weight and basic functions, it is necessary to pay attention to a peculiarity of this problem, which is the term proportional to the divergent of the strain rate derivative that exists in the transport equation. After applying the divergence theorem, the term is reduced to a second order derivative of the velocity field. As the basis functions used to represent the velocity field have discontinuous derivatives along the border of each element, it is necessary to represent the velocity gradient as an independent field with a continuous interpolation, called $\bar{\bar{G}}$. The model used in this work, which was also adopted by Silva (2013), is:

$$\bar{\bar{G}} = \nabla\vec{u} - \frac{\nabla.\vec{u}}{tr\bar{\bar{I}}}\bar{\bar{I}}. \tag{10}$$

The unknown fields are represented as a linear combination of basis functions. The basic functions used to represent the independent variables within each element are: $\varphi_j(\xi,\eta)$ biquadratic Lagrangian polynomials; for velocity and particle concentration field $\chi_j(\xi,\eta)$ discontinuous linear basis functions; for pressure $\psi_j(\xi,\eta)$ bilinear Lagrangian polynomials for the interpolated velocity gradient field. The coefficients of the linear combination of basis functions representing the discrete problem of unknowns are: $U_j, V_j, P_j, \phi_j, X_j, Y_j, Gux_j, Guy_j, Gvx_j$ and Gvy_j. The described basic functions are associated with a quadrilateral element of 9 nodes and 64 freedom degrees.

The system of partial differential equations is transformed into a system of nonlinear algebraic equations, solved here by Newton's method.

3. RESULTS

All calculations was performed keeping some of the parameters constant, they are: particles radius (a = 4 mm); channel height (H = 0.1 m); fluid viscosity (μ = 0.1 Pa.s) and particle concentration at the inlet of the channel ($\emptyset m = 0.3$). The unit system adopted is SI.

A mesh with 20 elements in y and of 50 elements in x was used in the calculations presented here.

3.1 Effect of varying of the particle density

In the analysis presented here, the channel length was 2 meters and the imposed pressure differential was *80Pa*. The diffusion coefficients were K_c e K_μ equal to *0.12* and *0.18*, respectively. The values of the dimensionless parameters are: $\lambda=0.66; Pe=5208.3$ and $\Delta P^*=282.84$.

It is observed in Fig. 6(a-c) that, as the particles density rises, they are deposited in greater amount on the bottom of the channel, because they start to suffer a greater influence of the migration effect due to gravity that pushes them down.

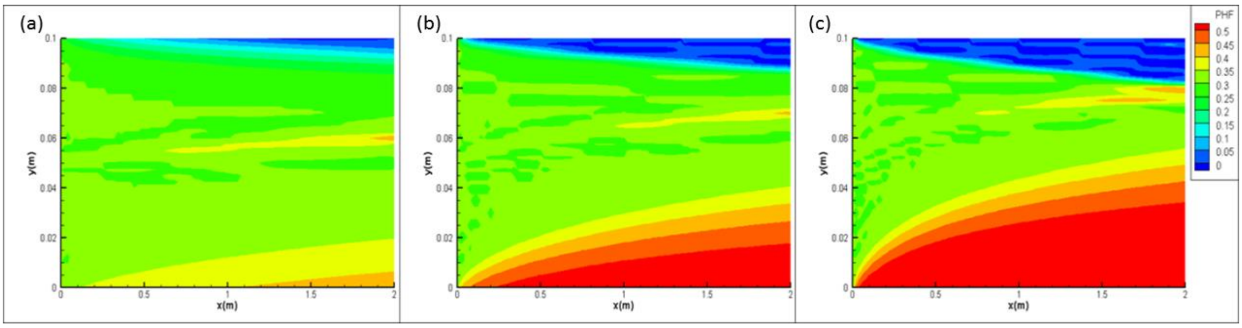

Figure 6 - (a), (b) and (c) are concentration profiles along the channel, *s* is worth respectively $2.79.10^{-5}$, $5.58.10^{-5}$ e $8.37.10^{-5}$.

Figure 7(a) shows the concentration profile in the outflow plane of the channel for different values of s. As s increases, the sedimentation effect acts more intensely carrying the particles to the bottom of the channel and the more particles are deposited. For these cases, the concentration in the base of the channel rises from 0.4 to 0.6, which is close to the critical value where the viscosity tends to infinity. In all the cases, it is possible to observe that in the top of the channel there is a region without the presence of particles, the concentration is equal to zero. For the last two cases there is a region near the bottom wall where the concentration is greater than *0.5*, what creates an almost static sediments bed. In all cases, there is a peak of particle concentration in the flow region, which is due to the migration effect influenced by the frequency of interaction between of the particles, which leads to the low shear region, and due to the effect migration influenced by the spatial variation of viscosity, which leads to the particles of high viscosity regions for the low viscosity region.

The differences observed in velocity profiles shown in Fig. 7(b), show that the change in the particle density promotes a change in flow, for a fixed value of pressure differential. With Q^* values equal to *1.2*, *0.92* and *0.65* respectively, it is true that as *s* rises, the flow decreases. This occurs due to blockage in the base of the channel by formation of the sedimented bed of particles.

As highlighted above, there is a certain concentration above which the viscosity of the suspension increases so rapidly that the suspensions behaves like a highly viscous fluid, which does not allow them to be transported by the fluid. Figure 7(c) shows the iso-line for $\emptyset = 0.5$, that represent the surface of the particle bed. It is noted that for $s = 2{,}79.10^{-5}$, the concentration along the channel is less than 50% and thus all particles flow freely through the channel, and as it increases the value of *s* the bed is being formed. In the case of larger values of *s* the bed are already blocks 40% of the output of the channel.

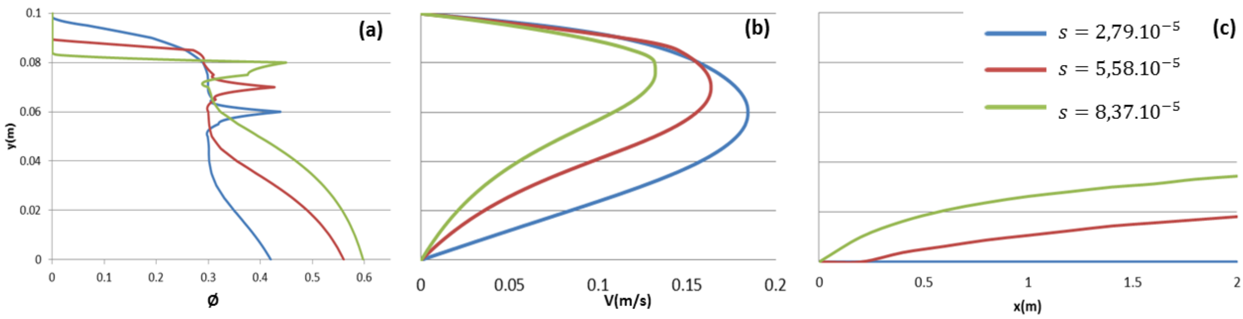

Figure 7 - (a) and (b) are the concentration and velocity profiles at the outlet of the channel, respectively, for the last three cases, and (c) iso-line Ø = 0.5, representing the surface of the particles bed along the channel.

As expected, the increase in density of the particles, without change in any of the other parameters, caused an increase in the dimensionless value of *s* which consequently showed that the sedimentation effect had a greater influence within the migration mechanisms, causing the formation a denser particle bed along the channel.

3.2 Effect of varying of the pressure

Varying the imposed pressure differential on the channel, will change the flow rate, as shown in Tab. 2. The other properties were kept constant: $K_c = 0.018$ and $K_\mu = 0.18$. The other two dimensionless parameters are $Pe = 34722.2$ and $\lambda = 0.1$. The decrease of the dimensionless s and the increase in the amounts of ΔP^*, shows the sedimentation effect loses forces between the migration mechanisms and a smaller amount of particles is deposited on the bottom of the channel.

Table 2 - Data from simulations that evaluate the variation of ΔP*.

ΔP*	*s*	Q*
282.84	$9.59.10^{-5}$	0.69
308.22	$8.08.10^{-5}$	0.73
353.55	$6.14.10^{-5}$	0.93
412.31	$4.51.10^{-5}$	1.06

It is observed from Fig. 8(a) a particles sedimented bed occupying almost 40% of the channel height. As imposed pressure differential rises the amount of particles that settles in the bottom of the channel decreases, whereas in the latter case that no particle is deposited, are all in suspension.

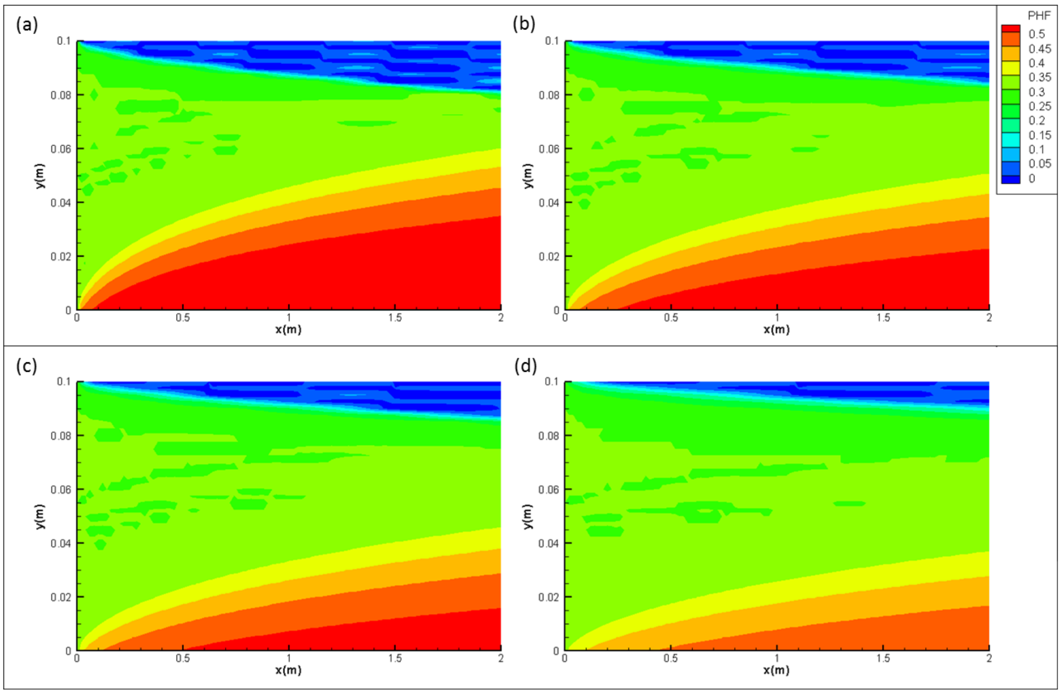

Figure 8 - Concentration profile along the channel for cases in which ΔP* is: (a) 282.84, (b) 308.22, (c) 353.55, and (d) 412.31.

The evolution of the particles deposition and, consequently, bed formation in the channel for different ΔP values is illustrated in Fig. 9. It is important to note that, in the last case the concentration along the channel does not exceed the value of 0.50, i.e. all particles are flowing together with the liquid phase. Also in this figure, it is observed that, shortly after half of the channel, the height of the particle bed follows a correlation, which is directly related to the flow rate and can be written in a generalized form as follows:

$$h = const.x^{0.5}. \tag{12}$$

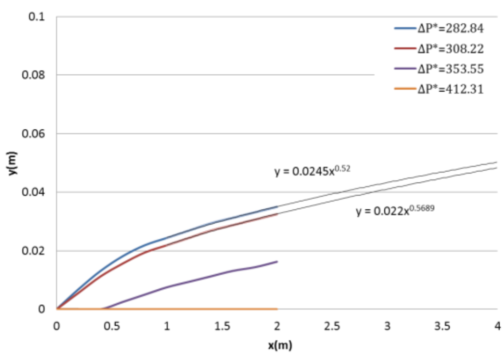

Figure 9 - Profiles that show the evolution of the formation of bed sediment (∅≥0,5) along the channel.

It is noteworthy that, this relationship is only true for the developing region of the bed, because as will be seen as the end of this section, there will come a point where this growth stabilizes, and a fully developed flow is reached.

For a high enough *s* and low enogh ΔP*, the flow reaches a fully developed condition, as shown in Fig. 10(a). The fully developed velocity and concentration profiles at *s=1.04.10*$^{-4}$ and Δ*P**1303.84* are presented in Fig. 10(c).

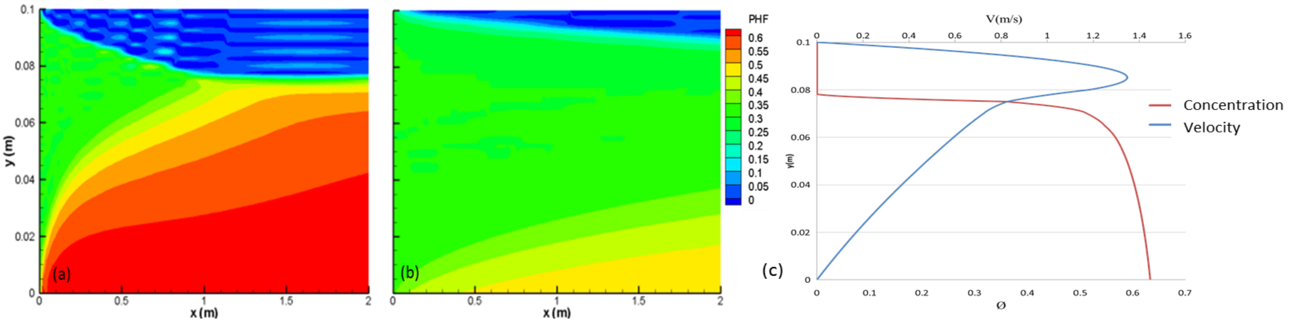

Figure 10 - Concentration profiles along of the channel for two different ΔP*, (a) 1303.84 and (b)1974.84 and (c) concentration and velocity profiles, to *s=1.04.10*$^{-4}$ and ΔP*=1303.84.

In order to verify a consistency in this behavior, both the pressure differential imposed and the particle density were increased. It is observed that beyond certain values of ΔP* and *s*, the profile at the outflow plane is the same, as shown in Fig. 11(a). Figure 11(b) presents the fully developed height of the iso-line $\emptyset = 0$ and $\emptyset = 0.5$ as a function of *s*. For $s \geq 4.5.10^{-5}$, all particles are suspended. For $s \geq 10^{-4}$, the flow is divided in two regions: the particle bed, with $h \approx 0.08m$ and a liquid flow particle free.

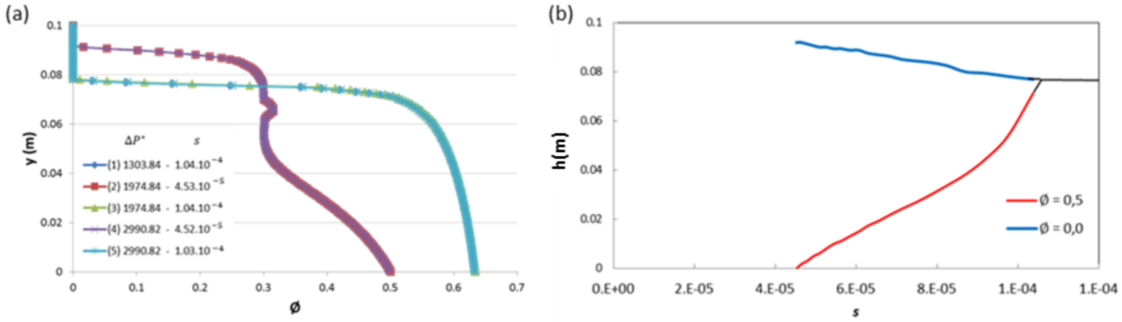

Figure 11 – (a) Concentration profiles in the output of the channel for the different values of ΔP* and s; (b) diagram depicting the relation between the bed height and the dimensionless parameter s.

4. CONCLUSIONS

Performing a simplified representation of the solid transport process, a two-dimensional laminar flow of solid particles suspensions between two parallel plates was studied. This study proposed the characterization of the flow evaluating solid particle migration considering three different mechanisms, that are due to the shear rate and viscosity gradients, and the density difference between the particles and the liquid phase.

The imposed pressure differential on the channel is responsible for the force which prevents the particles from settling and forming the bed. The larger the ΔP, the smaller is the particle bed at the bottom of the channel. Moreover, it was possible to determine a direct relationship between the height of the formed bed and the dimensionless parameter s, which is influenced by the pressure differential and particles density.

The results will be of utmost importance in the development of more accurate models describing solid transport process in annular well.

5. ACKNOWLEDGEMENTS

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