AADE-12-FTCE-43

A R&D Network on Drilling Hydraulics to Address Offshore Well Construction Challenges

Andre Leibsohn Martins and Raphael Padua Santos, PETROBRAS; Priscila Varges , PUC-Rio; Rosângela Z. Moreno, UNICAMP; Bruno V. Loureiro, UCL; Admilson Teixeira, UTFPR; Elie Padilla, UFU; and Sergio C. Magalhães, UFRRJ.

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This paper was prepared for presentation at the 2012 AADE Fluids Technical Conference and Exhibition held at the Hilton Houston North Hotel, Houston, Texas, April 10-11, 2012. This conference was sponsored by the American Association of Drilling Engineers. The information presented in this paper does not reflect any position, claim or endorsement made or implied by the American Association of Drilling Engineers, their officers or members. Questions concerning the content of this paper should be directed to the individual(s) listed as author(s) of this work.

Abstract

Hydraulics plays a major role in well construction, especially in narrow operational window scenarios, where the difference between pore and fracture pressures approaches zero. Besides, special geometry wells, where annular friction losses contribute expressively to downhole pressures, are becoming attractive alternatives to enhance production. Efficient drilled cuttings transport, minimization of contamination during fluid substitution operations and gravel packing are critical operations to be performed. The hydraulic targets for such projects require multidisciplinary technological development, including real time monitoring of downhole pressure, density and friction reduction concepts, chemicals and equipment, rheology optimization and reliable multiphase models. This article describes the fundamental and applied developed carried on by Brazilian universities and R&D Centers focused on well construction hydraulics. Main topics include rheology and complex liquid flows, solid – liquid flows, flows involving mass transfer and near wellbore flows.

Introduction

Around 90% of the Brazilian oil production comes from offshore fields as shown in Figure 1. Campos Basin is by far the major producing area. Espirito Santo and Santos represent relevant reserves for the future. For maximum reservoir exploitation and recovery factors in these fields, some of challenging environments or situations are faced. In most offshore scenarios, PETROBRAS faces deep (>800 m) and ultra deep (> 2000m) waters and reservoir related issues, such as salt drilling, non-consolidated sands, heavy oil reservoirs and heterogeneous carbonates. The present and future E&P challenges certainly demand expressive investment in logistics, infra structure, human resources and technology. More details are described in Martins et al (IADC 2011)

In the beginning of the century, the brazilian government ruled, through its national agency of petroleum, natural gas and biofuels, that 1% of the gross income from oil and gas fields should be invested in R&D projects within the Brazilian universities and R&D centers. The legal obligation created an unique situation which resulted in a boom in the brazilian academia with significant injection of material resources to create infra structure, develop research projects and form dedicated specialists. Between 2007 and 2009, PETROBRAS invested around 0.8 billion USD in the brazilian universities and research centers.

This article presents the technical scope of a relevant R&D network on drilling hydraulics which aims to support the challenges faced by the well construction in these environments. Officially nested on a well construction technology network, the projects on well construction hydraulics involve around 12 universities and technology centers and more than 600 people. Today, project involving around 13 million USD are under course, representing 30% of the total budget of the well construction technology network. Several results of this R&D effort are public and may benefit the well construction industry in general. Major topics covered include rheology, transient flows, solid liquid flows, well control issues, drag reduction, hydrates, Automation and control, Solids separation and drying and Drilling sensitive formations.

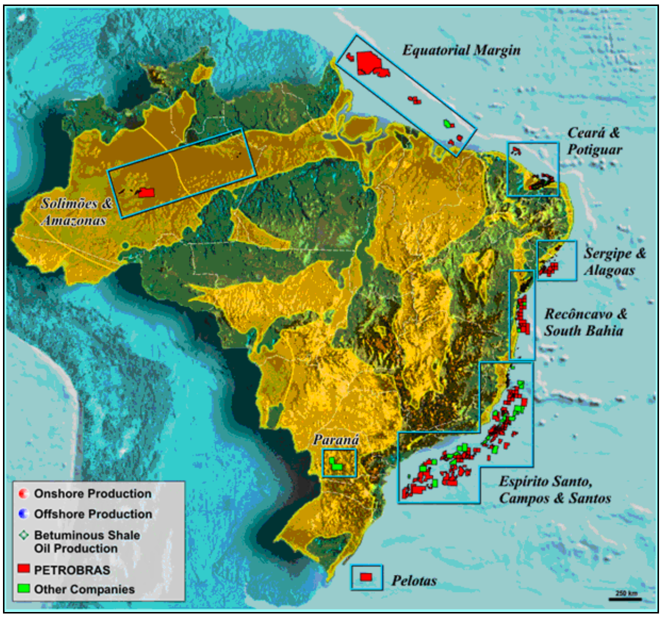


Figure 1 - Offshore and Onshore fields in Brazil.

Rheology and Complex Annular Liquid Flows

Special Topics in Drilling Fluids Rheology (Marchesini et al., 2010)

In oil industry, drilling fluids usually present a complex non-Newtonian behavior that must be precisely designed so as to ensure the safety and success of drilling processes. Actually, in order to perform the rheological characterization of a drilling mud, it is necessary to deal with some phenomena inherent to the rheometry of complex materials. Apparent wall slip, sedimentation of dispersed solids and evaporation of solvents are among the main problems found in the rheological characterization of such materials. In addition, there are challenges in the rheometry of this kind of material such as yield stress measurements and thixotropy that remain not fully understood. Therefore, a detailed investigation was performed on the rheometry of drilling muds and its main sources of error.

Figure 2 illustrates flow curves obtained with different geometries and the thixotropic curves obtained for the same mud with different shear rates. From these curves it is possible to note that an apparent slip region is clearly present, and that the cross-hatched-plates geometry is the most effective one to avoid apparent wall slip for this material. In the thixotropic curves obtained for the same mud with different shear rates it can be seen that for low enough shear rates an overshoot is observed, decreasing with a decrease in the applied shear rate.

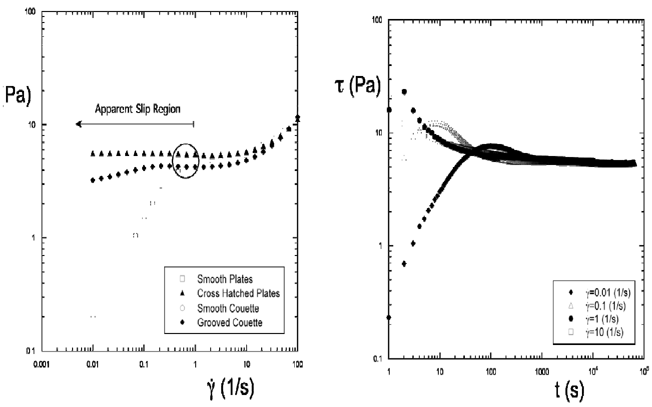


Figure 2 - Flow curves obtained with different geometries and thixotropic curves, respectively.

Flow Visualization and Simulation of Fluid Substitution in Drilling and Cementing Operations (de Souza Mendes, 2008)

Several dedicated visualization experiments were performed to investigate the displacement efficiency during the displacement by a Newtonian oil of aqueous solutions of Carbopol flowing through an annular space. The inner tube outside diameter of the annulus is 16mm, while its gap is 9 mm. The tubes are made of transparent glass to allow flow visualization. The Reynolds number is kept low for all cases investigated, to ensure negligible inertia. The apparatus was built in such a way that the interface is always flat at the startup of the flow. The orientation of the axis with respect to gravity is varied from 0 to 90°.

The main parameters that govern this flow are the orientation angle, the viscosity ratio, the density ratio, the flow rate, and the yield stress. In the experiments, the interface shape is recorded as it proceeds along the annulus for different sets of the governing parameters, and the displacement efficiency is determined.

The interface shape evolution for the case of one Newtonian liquid (glycerol) displacing another (lower viscosity oil) is illustrated in figure 3. This figure shows pictures of the interface at different times. The viscosity ratio ($N\mu = \mu 1/\mu 2$) was ≃ 8 and the density ratio was around 1.36. It can be seen that, for this combination of parameters, the interface evolves to a fixed shape, and the displacement efficiency is nearly 100%. Other experiments, including non Newtonian flows are available.

Numerical solutions were also obtained for comparison with the experiments realized in the pilot scale. It can be observed in figure 4 that the spacer material displaced the drilling mud with good displacement efficiency and a flat interface. It is also observed that the cement slurry displaced the spacer material in an efficient way.

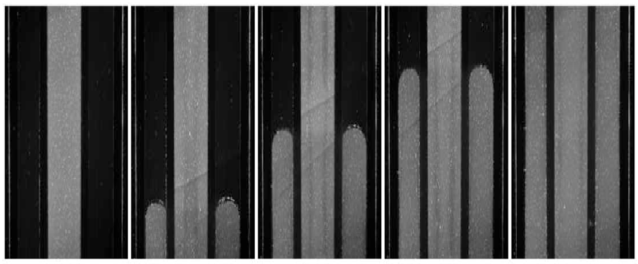


Figure 3 - Interface evolution - Newtonian liquid displacing a less viscous Newtonian liquid.

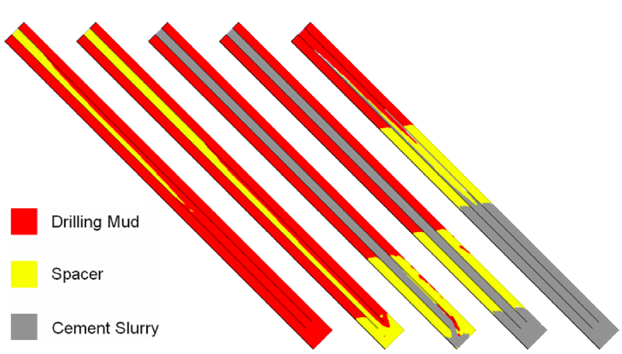
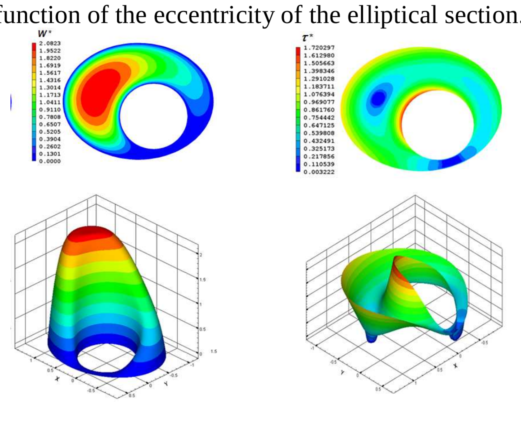


Figure 4 - Efficiency of the cement plug operation evaluated by numerical simulation.

Viscoelastic and Viscoplastic Flows Through Contractions and Elliptical Annuli (Ambrós et al, 2008; Alegria, 2011).

Drilling fluid flows through contractions and elliptical annuli are investigated numerically using computational fluid dynamics and experimentally employing a PIV stereoscopic system to obtain the velocity and shear stress fields. The aim was to understand flow through bit jets and annular flow in situations were wellbore ovalization occurs. Due to the presence of polymers and solids, viscoplastic and viscoelastic effects are expected in irregular geometries. Figure 5 illustrates one relevant line of this research line: this work presents an analytical and numerical study of the viscoplastic fluid flow, through concentric and eccentric elliptical annular cross sections ducts. The analytical solution employed is based on the slot flow model and the fluid flow was modeled as parallel plates in narrow annuli. For the numerical solution of the conservation equations, the finite volume method, the Hybrid interpolation schema and the SIMPLEST Method for the coupling pressure-velocity were used.

Expressions for relevant engineering parameters like volumetric flow rate, pressure drop and an expression to the friction factor were obtained. The results for the concentric and eccentric circular annulus are adequately reproduced when the elliptical cross section tends towards unitary aspect ratio. It is shown that the friction factor generally is reduced with increasing eccentricity and oval shape of the outer pipe. Also, it is discussed the existence of conditions where the friction factor increases as the oval shape of the external duct increases. In addition, we observed that the shear stress tends to increase at the major axis and decrease at the minor axis of the duct wall, i.e., the shear stress distribution along the wall is a function of the eccentricity of the elliptical section.



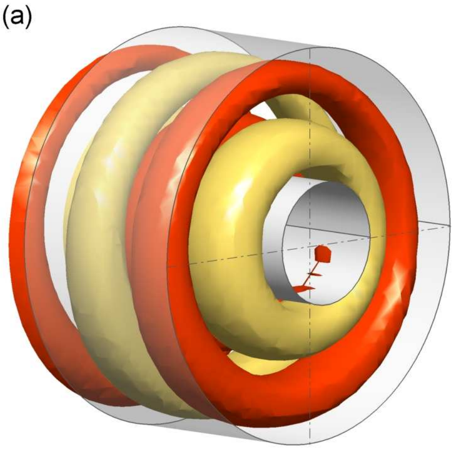
(a) (b)

Figure 5 - Viscoplastic elliptical annular flow - a) 3D axial velocity profile and b) 3D shear stress profile. The eccentricity of the internal pipe is $e^* = 0,7$. $r^* = 0,5$, $\varepsilon = 0,7$, $Bi = 0,3$ **and** $n = 0,6$.

Annular Flows with Variable Eccentricity (Padilla, 2008)

This work is an initial step on the development of a fluid structure formulation to represent the interaction between annular flows and drillstring dynamics. The strategy is to develop high performance solvers based on the immerse boundary method, accounting for laminar, transitional and turbulent flows of drilling fluids. At the present stage, newtonian flows in annular regions with a rotating internal pipe are considered. Translation and eccentricity effects are illustrated on Figure 6. The coherent results and agreement with other published material (Taylor- Couette and Taylor Couette with variable eccentricity) highlight the potential of the solver to reproduce more complex problems.

(a)



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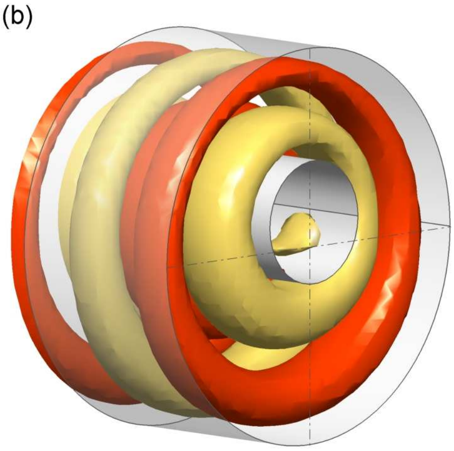

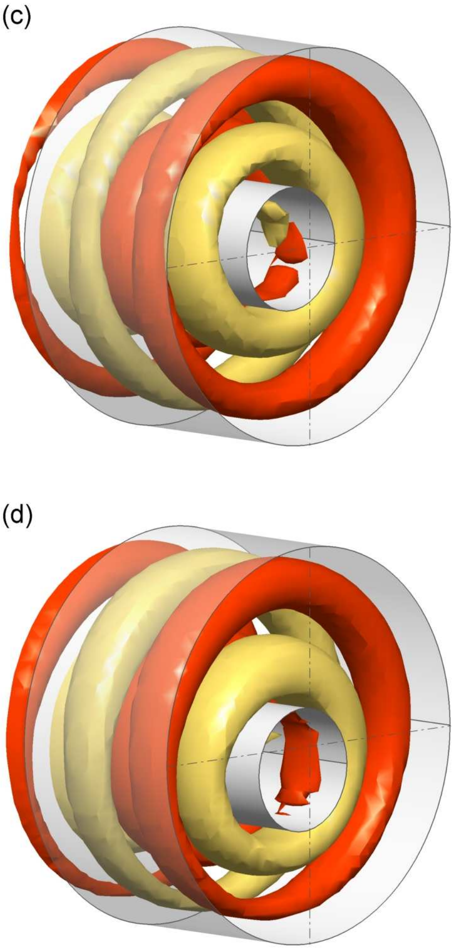

Figure 6 - Taylor-Couette Flow with variable eccentricity represented by instant axial velocity iso –surfaces. (a) 4 *s*, beginning of eccentric movement of internal pipe, (b) 4,1 *s*, (c) 4,25 *s*, (d) 4,35 *s*.

Pressure Transmission in Synthetic Fluids (Oliveira et al, 2012)

Pressure transmission issues in drilling fluids eventually present abnormal behavior which can be detrimental to several operations. In some situations, pressure fluctuations in bottomhole conditions are not immediately reflected in surface due to compressibility and/or to non Newtonian behavior of drilling fluids. This issue can cause delays in influx detection and generate safety issues. Additionally, pressure imposed at the surface may, in some conditions, be not fully transmitted to the bottom of the hole. In some situations, such as in use of hydraulically actuated completion valves an expensive fluid substitution process may be required to guarantee pressure transmission.

The purpose of the current work is to mathematically model the pressure transmission in drilling fluids compressed to open valves that are driven by pressure difference. The gelled fluid motion is considered isothermal, laminar and compressible and the governing equations of mass and momentum balance are solved numerically. A constitutive equation for gel breaking is proposed which is fitted to rheological data obtained in the lab. Additionally, the model results are corroborated with measured data obtained from a laboratory experimental rig (Gandelman et al., 2007). In such device, the drilling fluid is compressed into a 50m long pipe that is rolled in a coil format and pressure is measured in four different points along the coil, as shown in Figure 7. The coil is placed within a thermally isolated chamber where the temperature is controlled in the range of 4 to 50^{o}C.

Figure 7 - Experimental rig designed for pressure transmission measurements.

Transient Models for Tripping Operations (Fedevjcyk et al., 2012).

Tripping is a frequent operation during the well construction process. The axial motion of the drillpipe displaces the drilling fluid and pressure changes within the wellbore. A pressure increase is observed when the drillpipe is run into the well since the drilling fluid is compressed against the bottom. If the borehole pressure exceeds the formation pressure, a fracture may be induced, resulting in fluid losses. Conversely, if the drill pipe moves upwards the pressure in the well is reduced in an event called swab. Whenever this swab pressure reaches values lower than those of the rock pore, formation fluid influxes may occur.

Despite the large number of works found in the literature either dealing surge and swab as dynamic or stationary problem, no reference was found on the transient phenomenon in wells with annular cross-sectional variation. In order to fulfill this gap, the current work presents a dynamic mathematical model for surge and swab in wells with cross-section change. The drilling fluid can either be treated as Bingham or Power law fluid. The governing equations of mass and momentum conservation are solved by the Finite Volume Method (FVM) and solved iteratively. A comparison with measured data obtained in an experimental rig is performed showing good agreement, as depicted in Figure 8. A sensitivity analysis to show the influence of the annular cross section variation in the surge and swab phenomenon is finally presented. The results show that wells with varying cross section may present pressure peaks more pronounced than those with uniform section.

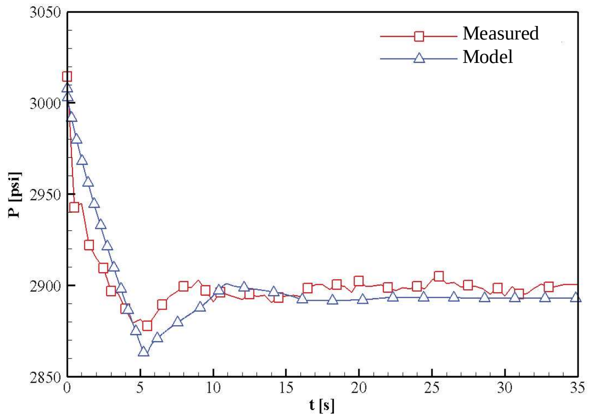

Figure 8 - Comparison between numerical and experimental pressure values of a swab test.

Solid Liquid Flows

Characterization of Drilled Cuttings

Cuttings size and shape are relevant parameters to several operations, such as cuttings transport, dispersion of cuttings plume in offshore environments and geochemical characterization. These parameters are a result both of the drilling process and of the traveling time between the bit and the surface. Main operational parameters which impact cuttings size are bit type, drilling fluid nature and of course, the rock formation itself. Tricone bits tend to generate larger cuttings than PDC, Synthetic fluids tend to preserve the cuttings while water based disperse them. Shale cuttings tend to be larger than sandstone and salt.

This line includes an extensive experimental campaign where cuttings have been collected, following a pre defined protocol, from different rigsites covering a range of fluid, formation and bit types. Later, in the lab, the samples were cleaned, dried, statistically treated to representative smaller samples before being submitted to the characterization process. A detailed image capturing and processing strategy was chosen to treat the samples. Figure 9 illustrates the images from shale cuttings drilled with PDC bits in the presence of synthetic drilling fluids. The cuttings have the following composition: 50% mudstones; 20% shale; 10% sandstone and 20% calcarenite.

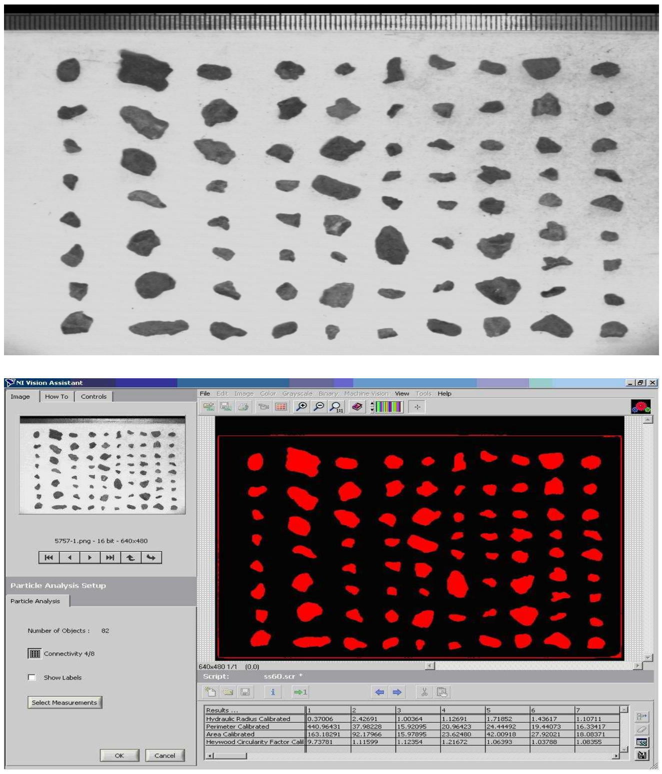

Figure 9 - Image processing for drilled cuttings transport characterization.

Rotation Effects on the Re-suspension of Cuttings Beds in Horizontal Wells (Loureiro et al., 2010)

Drill string optimization has been the target of several studies involving its influence on the suspension of cuttings found in the cuttings bed, the transport of cuttings, and loss of pressure. Since some studies found in industry literature exhibit divergence over the effect of the drill string rotation on the suspension of cuttings, this project is intended to quantify the capacity for suspension of particles from the cuttings bed for different fluids and different heights of sedimentation, in cylindrical horizontal wells. Such information is relevant to the well bore cleaning process and contributes to increased efficiency in the production of oil and gas (Figure 10)

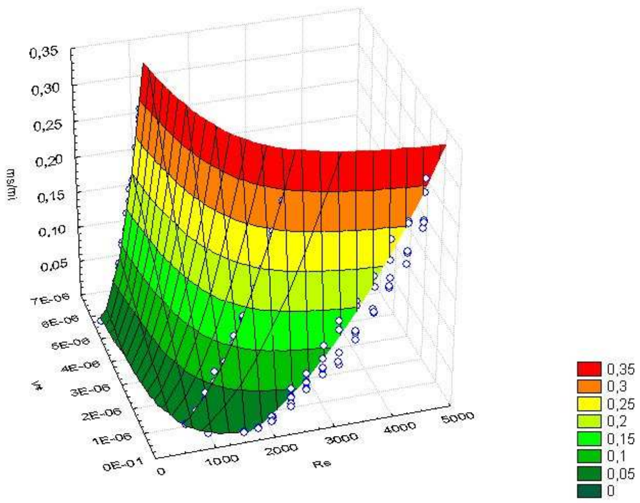

Figure 10 - Ratio of Suspended Mass to Reynolds to Dimensionless Kinematic Viscosity. 8 ½" Phase; height bed h/D=0.31 and mean particle diameter dm = 3.4mm. OD: 8 ½''. Column Rotation: 30 rpm. Axis: z = ratio between suspended mass and initial mass; y = dimensionless viscosity; x = rotational Reynolds.

Transient Cuttings Transport Models (Costa et al., 2008)

Drilling is essentially a transient activity, where ROP, temperatures, fluid properties, and other important aspects vary all the time. Most wellbore hydraulics design softwares consider steady state modeling. Real time hydraulics analysis requires dynamic models to represent pressure fluctuations. This line extends the concepts of 2 and 3 layer models to a transient formulation aiming real time hole cleaning diagnosis

Flows with Mass Transfer

Salt Diffusion Coefficients in Water Based Fluids (Souza, 2010)

One of the main challenges of the petroleum industry is the drilling in salt domes. The presence of salt zones indicates the possibility of the existence of petroleum, since the insulating properties of salt allow the formation of geologic traps that imprison the migrant oil. However, if it is not well designed, many problems may occur due to the diffusion of the salt in the drilling fluid, such as fracture of the region above the saline zone or even the collapse of the well. These problems may increase the costs of the drilling phase. The study of the impact of the drilling fluid used in salt regions is very important and, to make this analysis possible, it is necessary to know the diffusion coefficient *D* of the salt in this fluid.

This research looked for a method to determine the binary diffusion coefficient *D* of salts in liquids (especially in drilling fluids) not only accurately, but also in a reasonable time. We chose to use the Taylor Dispersion Method. This technique has been used for measuring binary diffusion coefficients in gaseous, liquid and supercritical fluids, due to its simplicity and accuracy. In the method, the diffusion coefficient is determinate by the analysis of the dispersion of a pulse of soluble material in a solvent flowing laminarly through a tube. A mathematical formulation for both Newtonian and non-Newtonian fluids was developed and a curve fitting function was proposed to determine the diffusion coefficient. The relevant sources of errors were also investigated. The experimental procedure and associated analysis were validated by applying the method in well-known systems, such as aqueous solution of NaCl, KCl and $CaCl_2$. Figure 11 illustrates some examples of the results obtained with Newtonian fluids.

The next step consists in investigating the diffusion coefficient of different salts in aqueous solutions of xanthan gum. The diffusion coefficient is a key parameter for the analysis of the leaching process which occurs while drilling and cementing salt domes with non saturated aqueous fluids.

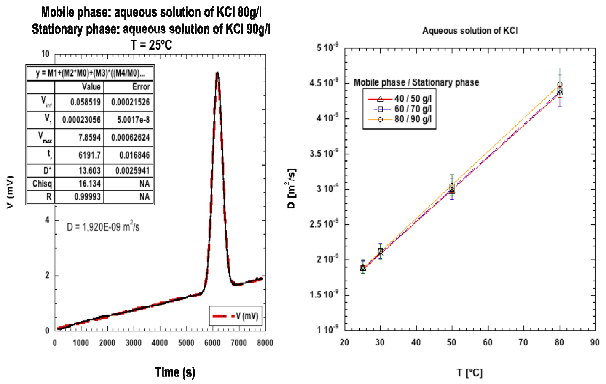

Figure 11 - Examples of results obtained with aqueous solution of KCl.

Kinetics of Salt Dissolution in Water Based Fluids (Magalhaes et al., 2011)

Salt cuttings will be gradually dissolved in non saturated fluids while they travel to surface. The velocity in which the salt is dissolved will directly impact the global salt concentration in the fluid and consequently, the diffusion phenomena from wellbore walls which is the main driving force for leaching. This study focus on the experimental determination of the kinetic parameters of salt dissolution in aqueous fluids. Data are obtained from an open circuit pipe flow (Figure 12) where samples are collected at different points and their salt concentrations quantified. Conventional kinetics relations are proposed to describe the phenomena.

Figure 12 - Salt dissolution unit.

Besides salt drilling, extensive experimental work have been conducted in the past regarding leaching of heavy oil reservoir zones while drilling with synthetic fluids (Costa et al, 2010) Dissolution of the native oil from the very unconsolidated reservoirs into the organic fluid was the driving force for the leaching process. CT scanning images would evaluate leaching while circulating the synthetic drilling fluid in front of a saturated non consolidated artificial core.

Near Wellbore Flows

Drilling fluid invasion into reservoir rocks is a major concern which may affect reservoir evaluation and generate damage. Waldmann et al (2012) describe corporate efforts to address the problem. R&D work within the Brazilian universities focus on different aspects, including the following.

Modeling and Experimentation of Drilling Fluid Invasion into Reservoir Rock

Based on injection experiments on real cores, several studies have been conducted in order to analyze the effect of drilling fluid properties and drilling program particularities on the invasion process. Moreno and Bonet (2010) present a comparison between experimental and simulated results for polymer based fluid flow through porous media. A traditional modeling based on Rapoport & Leas equation was numerically solved using a finite difference method and matching for saturation and pressure results were searched. However, it was shown that using just one representative fractional flow curve to forecast the invasion phenomena, instead of a family of curves, matches between modeling calculations and experimental data honor or saturation profile or pressure drop along the invaded zone. If gradient pressure were prioritized on the matching procedure, just a position for average saturation distribution can be determined. For accurate polymer based mud invasion representation, it was recommended to extend the approach and include instantaneous and local properties' changes.

LOPES et al (2011) discuss the topic of Natural Cleanup of Damaged Formations. In this work, polymer injection into the sample at residual water saturation has improved the reservoir representation; however, invasive fluid has displaced both mobile oil and initial immobile water. During the back oil flow, most of the invasive polymeric solution was produced back and saturation distribution was restored close to the original one. Local impairment conditions were calculated using differential pressure along the core and their values were compared with the average global value. Additional insights about dynamic mechanisms were also discussed based on a large quantity of monitored data.

Lopes et al. (2012) account for the damage resultant from the present of shale interlayers (which may be incorporated in water based drill in fluids) in sandstone reservoirs. This work is focused on formation damage analysis due to drilling fluids invasion in high permeability sandstone oil reservoir. Water-based fluids were prepared with the following components: distilled water, salt (NaI), polymer (Partially Hydrolyzed Polyacrylamide – HPAM, and Xanthan Gum - XG) and clay (Bentonite). Samples were submitted to an invasion process, simulating an overbalanced drilling, and to an oil reverse flow, simulating oil production beginning. Results showed that clay content fluids present lower loss circulation than fluids prepared only with polymer. Moreover, clay concentration influenced on permeability impairment and productivity ratio return results. HPAM fluids, when injected, invaded more samples than XG fluids, but productivity ratio return was also higher.

Silveira et al (2012) discusses invasion in heterogeneous reservoirs. This work aimed to compare the drilling fluids invasion and the reverse flow of oil in samples of carbonates and sandstones, searching the influence of rock type in formation damage and its interaction with the tested drilling fluid. The tests protocol including sample preparation, characterization of the multiphase flow, invasion of drilling fluid and the reverse flow of oil were performed in samples with same level of gas permeability. It was possible to observe that used carbonate samples were less water wet compared to sandstone ones, invasion of drilling fluid was faster in carbonate samples, however, during the reverse flow stage, productivity in this type of rock also has returned faster relatively to the sandstones samples.

Polymer Flow through Hele Shaw Cells (Varges et al., 2010)

The displacement of one fluid by another fluid in a porous media is frequently encountered in drilling fluid invasion through formation, groundwater movement, crude oil displacements, fracture conductivity, polymer processing, filtration, among many others. The Saffman-Taylor or viscous fingering instability occurs when one fluid pushes a more viscous one, and a Hele-Shaw cell is a convenient tool to the phenomenon observation. Specifically, the displacement of a non-Newtonian fluid by a Newtonian (and vice-versa) in a rectangular Hele-Shaw cell is analyzed both numerically and experimentally.

A fully 3-D numerical simulation of this displacement flow is also performed, using the finite volume technique and the Volume-of-Fluid method to solve the governing equations. The main parameters that govern this flow are the viscosity ratio, the rheological capillary number, and the (dimensionless) flow rate.

Experiments were performed using xanthan gum and a Newtonian mineral oil. The evolution of the shape of the interface was analyzed through a digital camera, as a function of the geometric, dynamic and rheological parameters. From tracing the shape of the interface, the displacement efficiency was determined. Thus, the spectrum of situations in which there is formation of fingers and plugs relating to displacement of xanthan gum by a mineral oil was defined. There is no universal convention in the literature for presenting the results so an original contribution concerns the proposed dimensionless parameters.

The main parameters that govern this flow are the dimensionless flow rate, the rheological capillary number and the behavior index of xanthan gum. It was observed that for a constant value of the behavior index and for a rheological capillary number of magnitude of 0.1, the displacement efficiency increases with the dimensionless flow rate, because the viscosity ratio decreases. Comparing the numerical and experimental results, the qualitative behavior is similar. Figure 13 illustrates cases with plugs and viscous fingers, respectively.

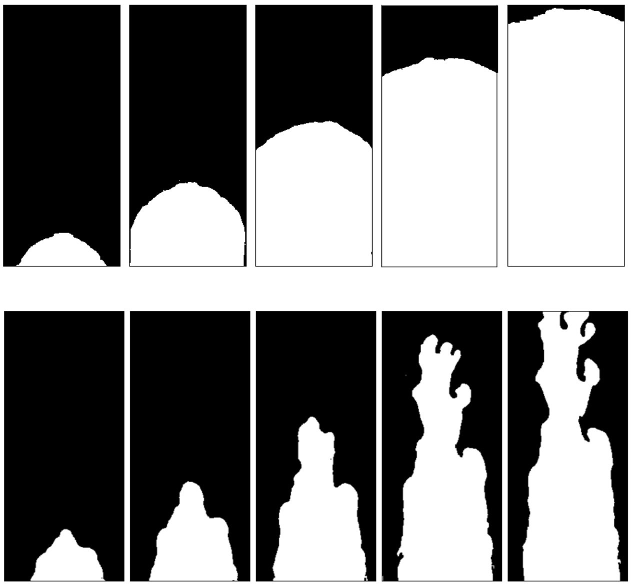

Figure 13 - Examples of different flow patterns of xanthan gum displacing mineral oil at different flow rates.

Modeling Dynamic Filtration While Drilling (Scheid et al., 2010)

Filter cake is a governing parameter which govern invasion. Normally drill in fluids contain bridging agents which are responsible for forming a low permeability cake on the surface of well walls and , consequently, control invasion. The axial flow of drilling fluid, on the other hand, erodes the bed and increase filtration. Scheid et al (2010) describe relevant modeling and experimentation on the process of dynamic filtration.

Drilling Fluid Invasion in Fractured Reservoirs

Losses control in fractured zones is a critical issue. De Lai et al, (2011) contribute with an interesting study on CFD simulation (Figure 14) and experimentation of the process. The goal is to provide optimization of particulate systems to control the losses.

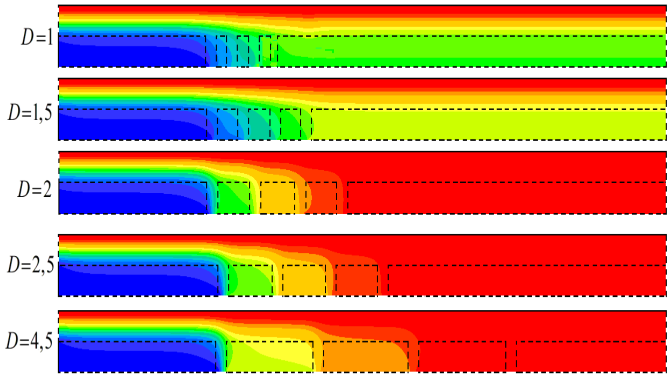

Figure 14 - Fluid streamlines inside fractures.

Water Block While Drilling Tight Gas Sands

Water block is a common and severe process of formation damage in tight sands. Andrade et al (2008) provide a relevant methodology based on capillary rise experiments (Figure 15) to address the problem. The methodology can orient in the role of surfactants on preventing this damage.

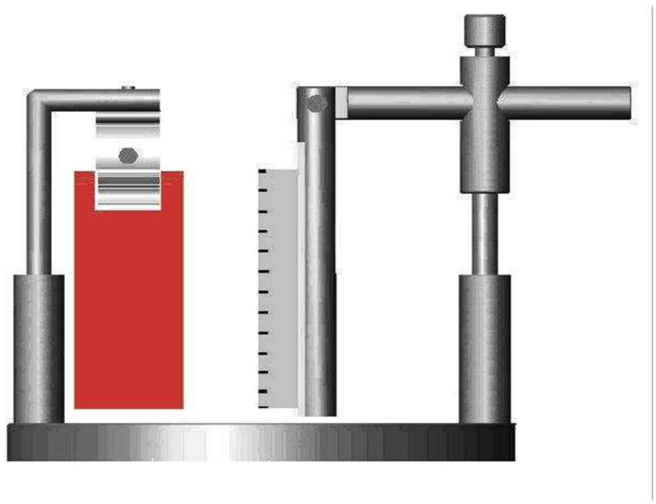

Figure - 15 - Capillary rise tests.

Final Remarks

Brazilian petroleum legislation provided a booming environment for R&D in the country, generated adequate infra structure in the local universities and technology centers and is contributing to the formation of technical and specialized professionals to be absorbed by the industry.

Relevant fundamental information generated by these projects is available in the national and international literature and the community is present in conferences in different areas including petroleum, rheology, chemical and mechanical engineering.

Several other topics relevant to the drilling fluid community are also under development and were not addressed in this article. Topics include hydrate prevention, cuttings separation and drying, additives (drag reducers, fluid loss controllers, etc), nanotechnology applications, online measurements, automation and control.

Acknowledgements

The authors wish to thank PETROBRAS for the authorization to publish and for the support for the R&D effort. Also, to the several (certainly hundreds) of other authors within the company and partner institutions, without whom all the development and implementation would not have been possible.

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