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WELL CONSTRUCTION HYDRAULICS IN CHALLENGING ENVIRONMENTS

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Abstract. *Hydraulics plaies a major role in well construction, especially in narrow operational window scenarios, where the difference between pore and frac 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, minimizing contamination in 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 monitoration of downhole pressure, density and friction reduction concepts, chemicals and equipment, rheology optimization and reliable multiphase models. This article focuses on the application of latest design, chemicals, software, and equipment technology for drilling and completing (including sand control) in challenging scenarios, such as ultra deepwater exploratory wells, extended reach offshore wells, 2000 m horizontal section in shallow water carbonate reservoirs, 1200 m horizontal section gravel packing in deep water non consolidated sandstone reservoirs, managed pressure drilling onshore experiences, extended reach onshore wells for offshore reservoir exploitation, including slant rig drilling and open hole gravel packing with synthetic low viscosity fluids. Finally, the hydraulic challenges for the future will be highlighted.*

Keywords: *hydraulics, sand control, friction reduction.*

1. INTRODUCTION

Around 90% of the Brazilian oil production comes from offshore fields Fig. (1). Campos Basin is by far the major producing area. Espirito Santo and Santos represent relevant reserves for the future. Other basins will be addressed in this work, Potiguar Basin and Reconcavo Basins, both mature areas in the northeast of Brazil. For maximize 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, reservoir related issues as: salt drilling, non-consolidated sands, heavy oil reservoirs and heterogeneous carbonates.

This articles summarizes PETROBRAS research and development efforts in association with a number of Brazilian universities, focused in advanced hydraulics concerns for a better of the phenomena involved. The strategy of deployment results passes through development of hydraulic models and simulators for complex wells. Friction loss prediction, transient flows, gelation, solid-liquid flows, sand control, fluid displacement through tubes and annuli are some of the topics.

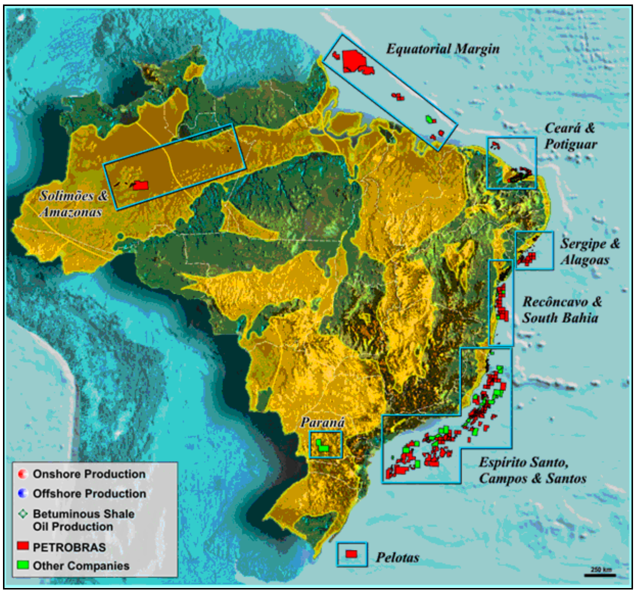

Figure 1. Offshore and Onshore fields in Brazil.

2. OFFSHORE/ONSHORE CHALLENGES

2.1. Offshore Challenges - Well Trajectory

In this section, the well paths associated with offshore scenarios will be presented. Water depths range from 500 to 3000 meters, while reservoir depths are normally around 3000 to 3500 meters. Normally the exploratory wells are drilled into this scenario Fig. (2a). Pre salt cluster reservoirs are deeper.

Some of the development wells are directional or horizontal. Horizontal sections ranging from 500 to 700 meters are common in deepwater developments Fig. (2b). The first challenge for well trajectory is associated to long horizontal sections. In heavy oil reservoirs, this is one of the strategies to maximize reservoir area open to flow and guarantee an economical flow rate. A big challenge is to drill and assure sand control in horizontal sections longer than 1200 meters, Fig. (2c).

Another big challenge is to drill extended reach wells in these deepwater scenarios. This strategy may be a good option for dry completion projects or even to consider shallow water vessels to drill deepwater reservoirs. A ratio of lateral departure over vertical depth bigger than 2 is considered to be challenging in deepwater scenarios, Fig. (2d).

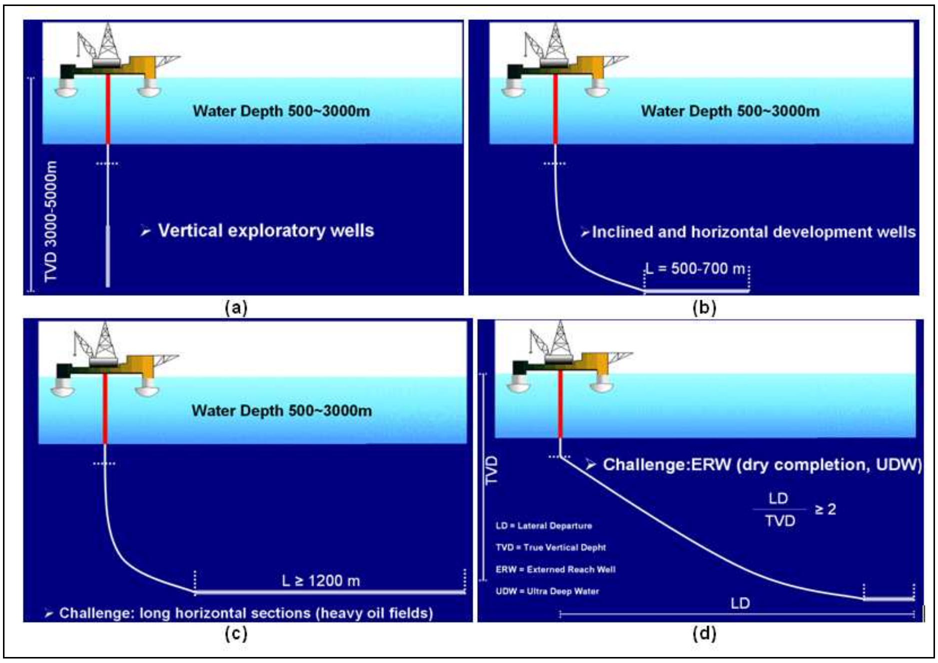

Figure 2. Typical and challengers scenarios for Brazilian offshore exploratory wells.

2.2. Onshore Challenges

Several onshore projects are also challenging. The developments of shallow water reservoirs from onshore locations often require special trajectory wells. Two good examples are the construction of short radius wells with slant rigs or extended reach wells in environmentally sensitive areas.

Normally, onshore projects get even more challenging considering economic aspects which rule onshore operations in Brazil. They are normally associated with low cost projects in which drilling equipment is far from ideal. Depleted reservoirs are also common.

3. HYDRAULIC CONCERNS

In this section, drilling, fluid substitution and completion issues will be addressed. The formation of a multidisciplinary team is a fundamental task to a challenging project concept. When geologists, reservoir engineering, drilling engineering, equipment and HSE personnel work together, chances of success increase dramatically.

3.1. Monitoring Pressures in Drilling Operations

The main goals of a good hydraulic project are to obtain proper hole cleaning, maintaining pressures inside the operational window. Another important issue is to make good use of real time monitoring of downhole pressures. There is a common sense in the industry that we have invested a lot in sensors, in data transmission but real time interpretation is still far beyond the desired levels.

Drilling hydraulics consists on a fundamental step on well design and, in several conditions, may limit the feasibility of the construction process. Dynamic pressures should be maintained inside the operational window defined considering pore, collapse and fracture pressures, guaranteeing that no influxes, losses or rock instability issues occur while drilling. Besides, minimum flow rates are required to assure that an adequate drilled cuttings transport occurs.

Downhole pressures are generated from two different origins: hydrostatic forces and friction losses. Hydrostatic depends on fluid density and vertical depth while friction losses depend on fluid density and rheology, flow rate, flow geometry and flow path. The following equations describe the correlation between the design variables and the downhole pressures.

$$P = P_h + \Delta P_f \tag{1}$$

$$P_h = \rho_{mix} \cdot g \cdot H \tag{2}$$

$$\Delta P_f = \frac{2 \cdot f \cdot \rho_{mix} \cdot v^2 \cdot L}{D} \tag{3}$$

The hydrostatic term depends on the solids concentration and solid density – fluid mixture in the wellbore annulus, and can be estimated by the following expression:

$$\rho_{mix} = \rho_{fluid} \cdot (1 - C_s) + \rho_{solid} \cdot C_s \tag{4}$$

The solids concentration, on the other hand, depends on the cuttings transport process, affected by fluid rheology, flow rate and wellbore geometry. In critical scenarios, where the operational window is narrow, annular friction losses start to play an important role in downhole pressures. This is especially critical in deepwater reservoirs, deep reservoirs and fields which require long horizontal wells.

Minimizing downhole dynamic pressures depend a lot on keeping good hole cleaning conditions by defining an adequate rheological profile for the fluid and using proper drillstring geometry. Normally, in overbalanced drilling operations, the fluid density is designed in a way that a comfortable overbalance between the wellbore hydrostatic pressure and the formation pore pressure. Several authors conducted experimental and theoretical works aiming the estimation of friction losses in pipe annular flows, besides restrictions. Silva and Matins (1988) and Subramanian et al. (2000) conducted relevant experimental work aiming the estimation of friction losses with commercial drilling fluids used in the 80's an the 90's.

In order to study the friction losses in tube, annular, tool-joints and stabilizers, a pilot scale flow loop was designed and is presented in Figure 3. Pipe diameters, pumping capacity and fluids were designed in a way that tests would dynamically represent drilling fluid flows at different portions of the circulation system. Aspect ratios simulating typical 12 ¼ in and 8 ½ in drilling configurations and Reynolds Numbers ranging from 500 to 5000 support the concept of physical and dynamical similarity between flow loop and wellbore data. Details about this work can be viewed in Rocha et al. (2008) and Scheid et al. (2009).

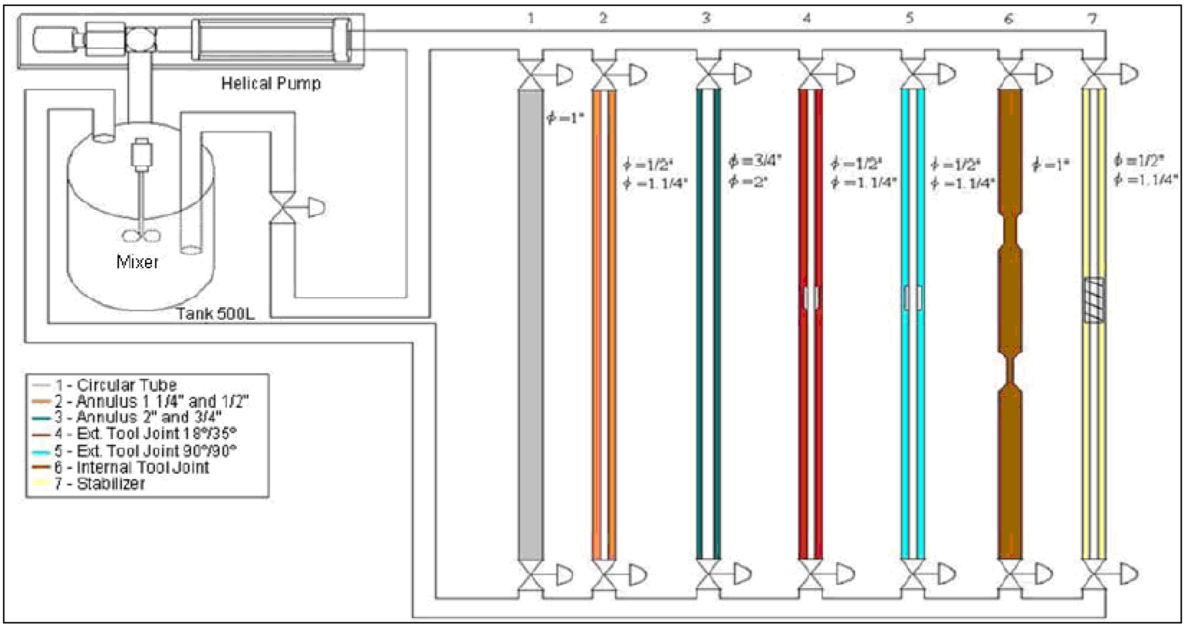

Figure 3. Scheme of experimental unit of fluids flows.

This experiment allows to determine among the equations available the most accurate equation for friction losses in laminar or turbulent flows besides the friction losses equations for external and internal flows through tool-joints and stabilizers.

The experimental unit for pressure control is presented in Figure 4. This unit seeks to describe the mechanisms and stages of drilling, showing the effects of disturbances in the control of pressure in the well, by handling some variables like flow rate or fluids density. Regarding the study of automatic control of pressure, strategies using different manipulated variables, such as density/composition, flow rate of drilling fluid, drill string rotation speed and opening the choke valve at return lines are being investigated.

A classic PI(proportional-Integral) controller approach was adopted to regulate the pressure bottom during the drilling job. The control scheme used a phenomenological model of flow gas-liquid-solid parameters grouped. In addition, an empirical model based on neural network, was also developed from experimental data obtained by PWD – Pressure while drilling measurements (Vieira, 2009).

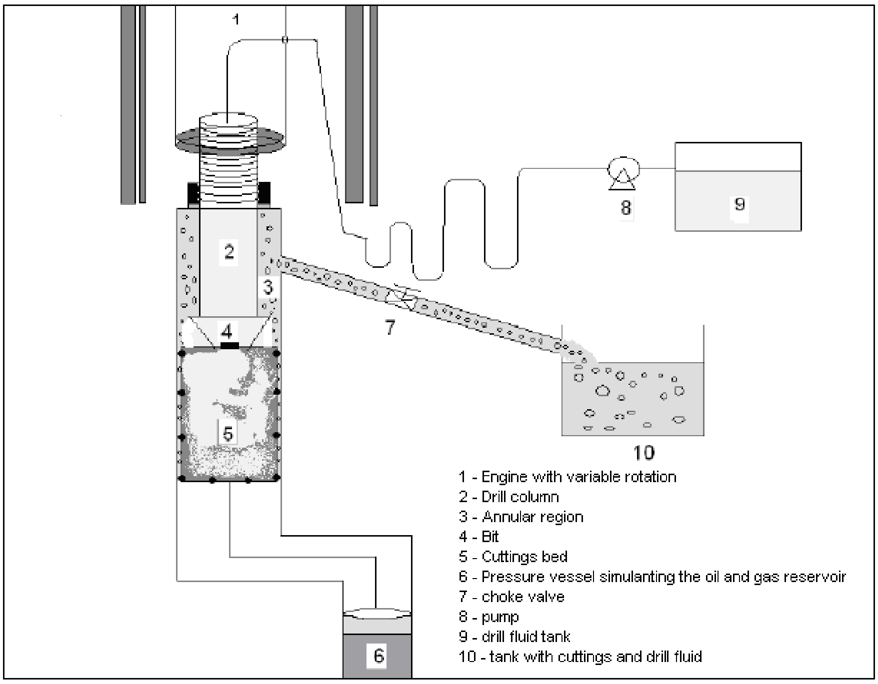

Figure 4. Scheme of experimental unit for pressure control in drill operations.

3.2. Peak pressure in the restart of circulation

This part of work aims to model the propagation of pressure when circulation is resumed. The gelled fluid requires an extra energy before it starts moving, generating a pressure peak. The problem is shown in Fig. (5). Mathematical modeling is fundamental to understand and predict pressure peaks during fluid flow start-up. Some studies are found in literature, but most of them are dedicated to low temperatures waxy crude oils start-up. Gel effects can both generate excessive pressures (inducing losses) and cause delays in pressure transmission which can directly affect gain detection devices. The current work presents a compressible transient flow model of the restart of drilling fluid circulation, in order to predict pressures at the borehole. The model comprises the conservation equations of mass and momentum which are solved by the finite volume method. A constitutive equation is employed to model the time dependent rheology of gel breaking (Negrao et al. (2010)).

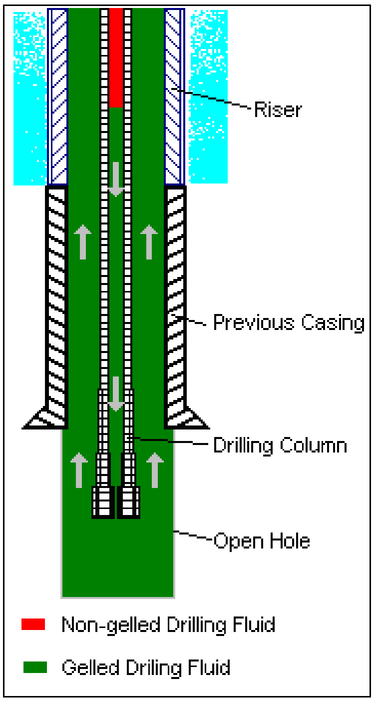

Figure 5. Restart of the circulation of drilling fluid.

The model considers the fluid flow will occur immediately if the pump pressure is sufficient to overcome the limit gel tension (the tension required to break gelled structure). If the pressure generated by the pump is lower than the limit tension, but higher than the dynamic tension, the gel is not broken immediately, but begins to undergo plastic deformation and stress fracture of the gel decreased with time. After some time applying pressure, the gel will fracture and the flow starts late.

3.3. Re-suspension of cuttings bed in horizontal wells.

The objective of this development is associated with the need to better understand the effect of some variables in solids removal while drilling wells.

Thus, the studies presented in this article complement the development of drilling hydraulics reseach. Some of them are listed bellow:

i) Granulometric characterization;

ii) Study of the suspension of gravel deposited in sedimented bed in horizontal wells;

iii) Determination of minimum shear stress for particle re- suspension;

A methodology was developed for characterization of cuttings obtained from samples returning from offshore wells (Loureiro et al. (2009)). Field samples are analyzed in the laboratory by means of a workstation to capture and image processing.

The objective of this study is to determine the size distribution as well as the roundness of the produced cuttings on the function of the following variables:

drilling fluid;

geology;

bit type;

Figure 6 shows a result of the probability density function for a sample of gravel obtained from the well of Espirito Santo basin.

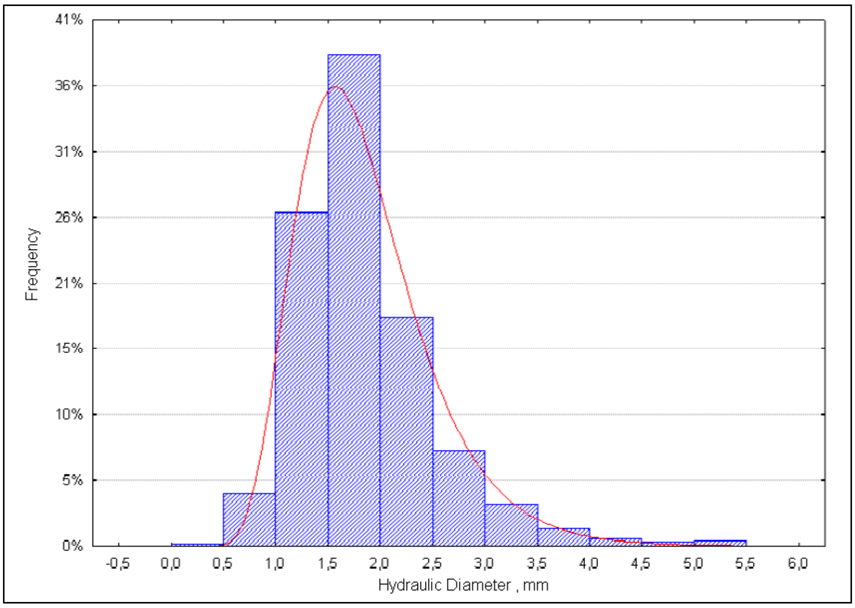

Figure 6. Chart Lognormal for hydraulic diameter of cuttings obtained for a well of Espirito Santo basin.

It is known that the suspension of this gravel bed is a function of several parameters, such as drillpie rotation, drilling fluid rheology, gravel size, among others.

From this problem, two simulators were constructed and instrumented to study the effect of the parameters mentioned in the ability to suspend particles. Figure 7 presents a picture of simulators. The analysis is done from the images captured by a camera set up for short exposure time for image capture.

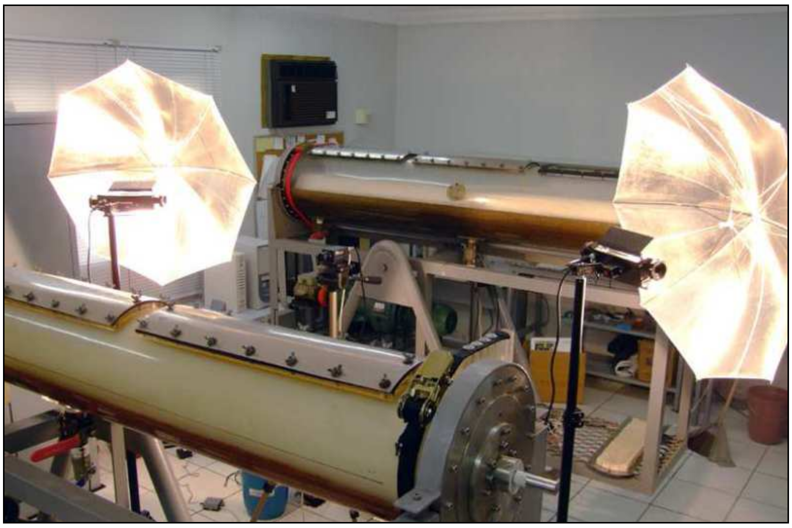

Figure 7. Experimental apparatus for study of re-suspension of cuttings bed in horizontal wells.

At this experiment it is possible to measure the lifting capacity and estimate the cleaning efficiency of a well from the rotation of the column and other parameters such as particle size and fluid viscosity.

The proposed project is to model the physical problem of flow in a horizontal well and the re-suspension of cuttings bed with simplifying assumptions. The methodology adopted for solving this problem is to use an experimental apparatus with flow control for indirect determination of shear stress by means of numerical simulation.

3.4. Transient model for cuttings transport in horizontal and inclined wells.

The proposal of this study is to develop a transient model for cleaning wells and drilling hydraulics, implemented in a numerical simulator (Costa et al. (2008)). The model is based on the principles of conservation of mass and momentum of the phases present in the flow, and is able to predict transient effects caused by several operations on drilling such as:

i) Operational parameters, flow rate, rate of perforation, drilling fluid;
ii) Drilling column movement;
iii) Bit jets obstruction;
iv) Washouts;
v) Fluid losses;

Model Features:

- Model of two layers as shown in Figure 8.
- Constitutive equation for re-suspension of solids.
- Fluid with uniform velocity in the section of the pipe.
- Sliding between solid and liquid phases in the regions of the bed and suspension.
- Model developed for all sections of the well - without discontinuities

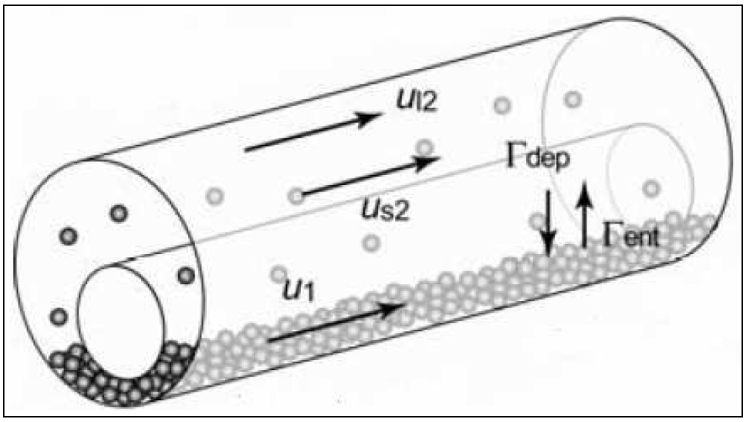

Figure 8. Scheme of model of two layers.

3.5. Fluid Displacement

There are two specific situations where minimizing contamination while displacing fluids is mandatory. First when displacing a synthetic drilling fluid by water, there is a tendency of contamination in the riser, due to the low annular velocities. Excessive amount of contaminated fluids may generate environmental concerns and additional transport costs. Simulating the substitution process consists on complex two phase flow transient CFD analysis (Dutra et al. (2005)). Figure 9 presents example results for simulations, showing the amount of synthetic fluid at the riser outlet. The unsteady behavior in all the curves where direct contact between chemical wash and synthetic fluid occurs denotes high degree of contamination. In the simulations where a spacer fluid is added there is an abrupt decay in the amount of synthetic fluid leaving the riser annulus. This behavior denotes a plug type displacement, minimizing contamination. Results indicate the poor displacement efficiency in the riser annulus when direct contact of wash and synthetic fluids occur. The increase of flow rate enhances but seems not to solve the undesired contamination problems. The introduction of a viscosified spacer seems to be a nice alternative to optimize the process.

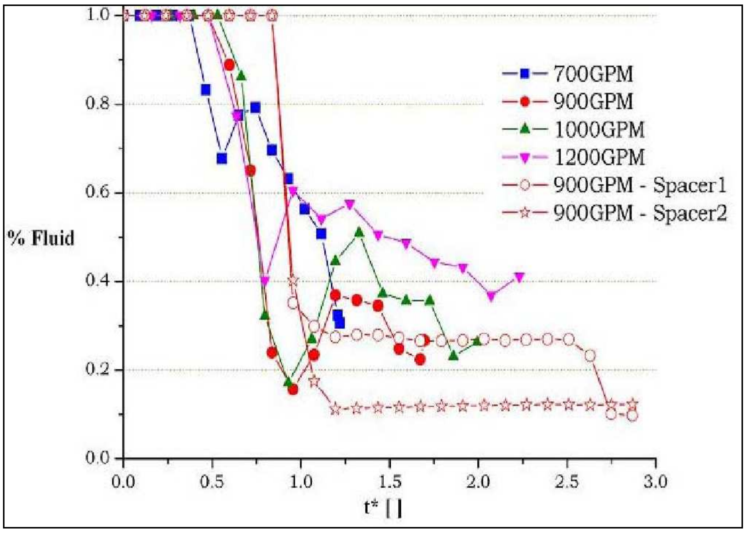

Figure 9. Chemical wash displacing a synthetic fluid in a riser.

Another important situation is the substitution of the drill-in fluid by a solids free completion fluid in open hole horizontal sections. In this case, any portion of the drill in fluid left in the well may have detrimental effect in well productivity.

Figure 10 shows the simulations and cross sections for the three annular flow in annular flow for the 8 ½”, fully eccentric, with different flow rates.

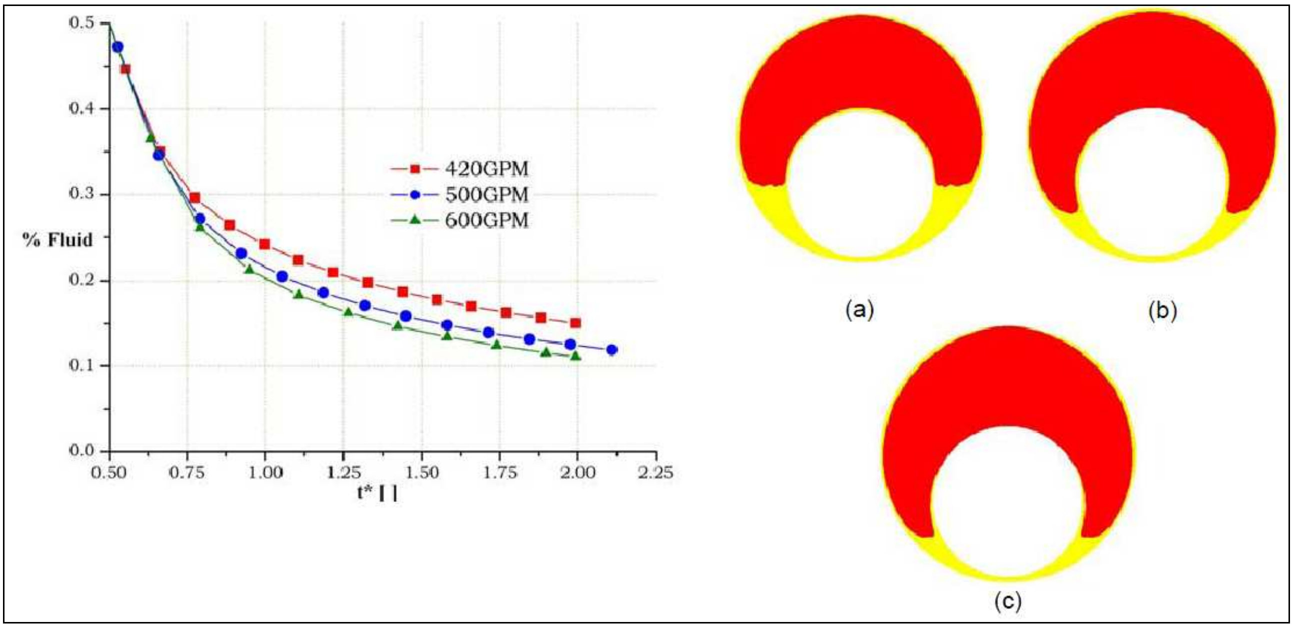

Figure 10. Completion fluid displacing(red) drill-in fluid(yellow) in horizontal 8 ½” – 5” annulus, fully eccentric, for different pump rates, cross section in the middle of the geometry, Pump rates – (a) 0,0265 m^3s^{-1} (420 gpm), (b) 0,0315 m^3s^{-1} (500 gpm) and (c) 0,0378 m^3s^{-1} (600 gpm).

Results indicate that displacement in the fully eccentric annulus is poor, with drill-in fluids remaining in its lower portion.

Such phenomena require complex CFD – computational fluid dynamics simulation as well as flow visualization experiments. The results from this modeling and simulation work can than be transformed in operational procedures for the field.

3.6. Open Hole Gravel Pack

This is the major sand control strategy adopted by PETROBRAS in offshore horizontal wells. The operation consists of fulfilling the open space between the wellbore walls and the production screens with a sized gravel, generating a high permeability pack, which would be able to allow oil production and restrict sand (Martins et al, (2009)). The conventional operation is based on the conventional alpha – beta wave placement and is associated with large pressure drops at its final steps: during beta wave placement, the flow is diverted to the narrow annulus formed by the screen and the washpipe. In long horizontals wells, downhole pressures may exceed operational limits. Like the workflow detailed for cuttings transport, the R&D work for gravel packing starts with the basics. Due to the similarities in the processes the mechanistic layered model was adapted to predict now the pressures governing the gravel placement operation. The physics behind a cuttings bed formation while drilling presented evident analogies with alpha wave deposition in gravel pack operations. Real scale experimental validation and software development were also part of the process.

The main goal of a design software for gravel pack applications is to provide a variable flow rate pumping schedule which guarantees pressures within the operational window an example of software results are presented in Figure 11. In situations where the operational window does not allow total gravel packing, special techniques are available. In such techniques, different solutions are provided to allow gravel packing and several of them, such as the use of lightweight proppants, proved to be effective.

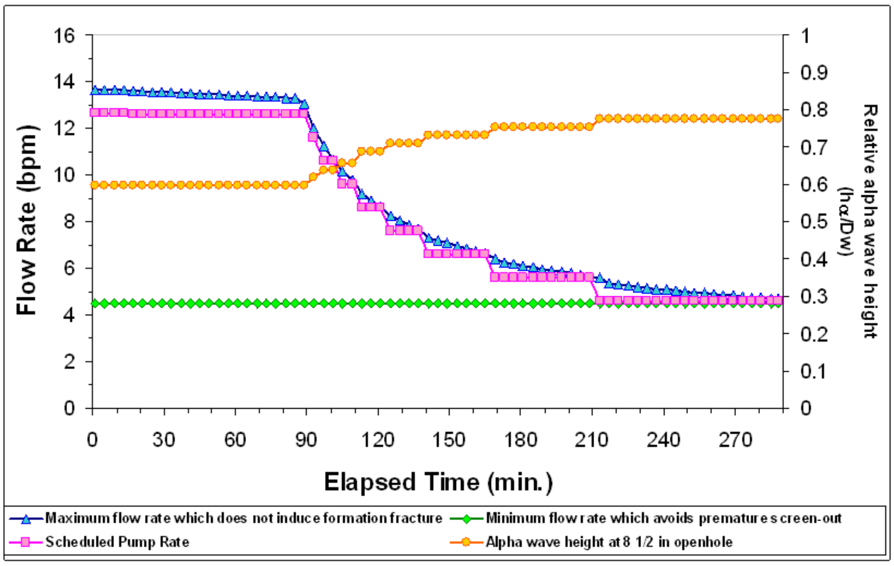

Figure 11. Variable Pump rate schedule.

4. RELEVANT FIELD RESULTS

Expressive field results include:

i) More than 270 Open Hole Gravel Packs in sections as long as 1200 m.
ii) Exploratory drilling in sub-salt / Ultra Deep Water environments.
iii) Offshore Extended Reach Wells (LD/VD=1,73, WD=1217 m).
iv) 2000 m horizontal section in shallow water carbonate reservoirs.
v) Managed pressure drilling onshore experiences.
vi) Extended reach onshore wells for offshore reservoir exploitation (LD/VD=3,3).
vii) Slant rig drilling Extended Reach Well - (LD/VD=10).
viii) Open hole gravel packing with synthetic low viscosity fluids.

5. FINAL REMARKS

The issues listed here represent a step forward in modeling hydraulic drilling and completion. The grounds and results of each project are essential for the development of studies and scientific softwares for specific operations such as gravel pack, fluid displacements through pipes and annuli and cuttings transportation in drilling horizontal and inclined wells.

The technology is ready to drill and complete long horizontal section wells in narrow operational window scenarios. Different alternatives have been proved and we are at the moment discussing with the assets convenient scenarios to apply them in horizontal sections of fifteen hundred meters or longer.

The future scenarios present additional challenges which need to be addressed, such as losses in fractured reservoirs and the construction of horizontals and ERW in sub salt environments. All technological limits will have to be pushed to develop economically the new discovered fields.

Offshore multilaterals are also a technological alternative with needs improvement. Although very attractive in the reservoir engineering point of view, the massive practice has been delayed due to difficulties in some completion and workover operations.

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