UNDERSTANDING DRILL IN FLUID INVASION IN MULT LAYER RESERVOIR SATURED BY COMPRESSIBLE FLUIDS

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Abstract. *Minimizing fluid invasion is a major issue while drilling reservoir rocks. Large invasion may create several problems in sampling reservoir fluids in exploratory wells. Besides, drilling fluid invasion may also provoke irreversible reservoir damage reducing its long term productivity. A common practice in the industry is the addition of bridging agents in the drilling fluid composition, such as calcium carbonates. Such products would form a low permeability layer at the well walls which would control invasion.*
This paper presents a radial model, based on Darcy's law to predict the drilling fluid invasion profile into an multi layer reservoir rock saturated with a compressible fluid. Results highlight that the differential pressure, the fluid compressibility, filter cake permeability and rock properties are important parameters that affect significantly the invasion profile. The proposed methodology is a tool to optimize drilling fluid design to be used in the drilling of reservoir sections in both exploratory and development wells in Campos Basin, offshore Brazil.
The process analysis is illustrated with a series of case studies in offshore exploratory wells drilled in Brazil. The analysis highlights the importance of filtration control and of a dedicated drilling fluid design for each specific reservoir.

***Keywords**: Drilling fluid invasion, fluid compressibility, flow through porous media*

1. INTRODUCTION

Offshore oil well drilling jobs are time consuming and expensive operations in which to minimize drilling fluid filtrate invasion and formation damage is a very important task to guarantee the original reservoir rock properties.

Drilling fluids are designed to ensure a fast and safe drilling operation and therefore must have consistent operational cost, to stabilize mechanically and chemically the well walls, to keep solids in suspension during pumps off periods, to facilitate the separation of solids generated by bit and facilitate geological interpretations of the material removed from the well.

Drilling fluids must also present some basic functions (Thomas, 2001):

- Exert hydrostatic Pressure on the formations to prevent the native fluids influxes, which can lead to serious security problems for the rig team.
- Maintain the physical integrity of the well preventing a possible collapse, especially the more friable formation.
- To remove solids generated by the bit.
- Cooling drill bit and lubricating drillstring.

In a conventional drilling job, the bottom hole pressure must be kept between pore and fracture pressures in order to prevent undesirable influxes and formation fracture. Such influxes would cause serious security problems for the rig team, since they are usually highly flammable hydrocarbons. Moreover, as the pressure differential from the well to formation is always positive, the fluid will tend to invade the reservoir rock (Figure1).

The drilling fluid filtrate invasion can cause irreversible damage to the reservoir, reducing its original permeability and affecting the well and/or field production profile (Jiao and Sharma, 1992, Moreno et al., 2009).

In development wells, the quantification of drilling fluid invasion can help to define the volume of acid to be pumped (used to reduce the damage), reducing time and operational costs (Pereira et al., 2007).

In exploratory wells during the sampling operation the drilling fluid filtrate invasion into reservoir increases the operation time and the possibility of contaminating samples. Inadequate fluid sample, in exploratory wells, can lead to inaccurate information about the economic viability of the reservoir development (Coelho, 2005). In heavy oil reservoirs, oil and filtrate interaction may generate stable emulsions, reducing its initial and/or its long term productivity. Invasion in light oil reservoirs is less critical due to its good mobility properties. Other critical scenario is the low permeability gas reservoirs where imbibition effects may result in deep invasion, causing a phenomenon known as water blocking, dramatically reducing production (Ding, 2006).

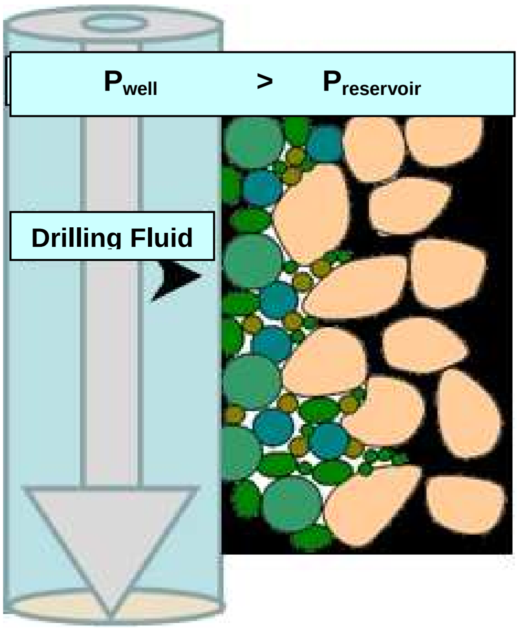

Figure 1. Drilling fluid invasion through the reservoir rock

This paper aims to provide a numerical simulation methodology to predict the drilling fluid filtrate invasion in a multi layer porous medium satured by compressible fluid and to evaluate the impact of the main operational parameters in the invasion profile, such as filter cake permeability, reservoir permeability, overbalance pressure, fluid density and oil compressibility.

2. MATHEMATICAL MODELING

The mathematical modeling to represent the flow through porous media is based on the continuity equations, represented by mass conservation equation, Darcy's law (1856), and equations of state, which for liquids is the equation of compressibility. The method used for discretization of partial differential equations described in the mathematical modeling was the finite volume. In this method each calculated property is located in the center of the discretized cells and the flow is located on the borders between the cells. In the present study, the two-phase flow (oil and drilling fluid), transient, two-dimensional cylindrical coordinates (axial and radial) and isothermal was modeled and analyzed. The differential equations shown below describe mass conservation in the oil phase and the global mass conservation, respectively.

2.1. Mass conservation equation to oil phase

$$\frac{\partial(\phi\alpha_o\rho_o V)}{\partial t}+\frac{\partial(\rho_o v_{o,r}A_r)}{\partial r}+\frac{\partial(\rho_o v_{o,z}A_z)}{\partial z}=0 \qquad (1)$$

2.2. Global mass conservation equation

$$\frac{\partial(\phi\rho_m V)}{\partial t}+\frac{\partial(\rho_o v_{o,r}A_r+\rho_f v_{f,r}A_r)}{\partial r}+\frac{\partial(\rho_o v_{o,z}A_z+\rho_f v_{f,z}A_z)}{\partial z}=0 \qquad (2)$$

2.3. Darcy's law

For the calculation of flows in porous media Darcy’s law was used. Superficial velocities are divided into axial and radial, according to Equations 3 and 4. Potential term (Equation. 5) is represented as a function of pressure and height..

Radial velocity:

$$v_{f/o,r} = -\left(\frac{K.k_{r_{f/o}}}{\mu_{f/o}}\right)\frac{d\Phi}{dr} \tag{3}$$

Axial velocity:

$$v_{f/o,z} = -\left(\frac{K.k_{r_{f/o}}}{\mu_{f/o}}\right)\frac{d\Phi}{dz} \tag{4}$$

Potential term:

$$\Phi = P - \rho_{f/o}.g.\Delta z \tag{5}$$

Boundary condition:

$$v\Big|_{r=\text{raio\_interno}} = -\frac{k_r.\overline{K}\,(t)}{\mu}\frac{dP}{dr} \tag{6}$$

Boundary conditions in the reservoir layers for z = 0 z = H, are zero flow, because it considers the isolated layers.

$$v\Big|_{z=0} = v\Big|_{z=H} = 0 \tag{7}$$

Absolute average permeability

Absolute average permeability is calculated as a set of resistance in line (Ahmed, 2002). In this case, the equation is a function of: reservoir and filter cake permeabilities and well geometry.

$$\overline{K}\,(t) = \frac{\ln\left(r_{ext} \big/ r_{torta}\,(t)\right)}{\dfrac{\ln\left(r_{\text{int}} \big/ r_{torta}\,(t)\right)}{K_{torta}} + \dfrac{\ln\left(r_{ext} \big/ r_{\text{int}}\right)}{K_{reservatorio}}} \tag{8}$$

Filter cake radius

Equation 9 is a function of fluid volume invaded, filter cake porosity and solids concentration of the drilling fluid (Waldmann, 2005).

$$r_{torta} = \sqrt{\left(r^2{}_{\text{int}}\right) - \frac{V_f\,(t)}{(1-\phi_{torta})\pi L}\left(\frac{C_s}{(1-C_s)}\right)} \tag{9}$$

3. NUMERICAL SIMULATION METHODOLOGY

The discretization method used to solve the partial differential equations was the finite volume. The finite volume method is a classical approach to solve fluid flow problem. With this method it is possible to guarantee the conservation of the flows of input and output for each control volume. In this method, each calculated property is located in the center of the discretized cells and the velocity is located on the borders between cells. Equations 10 and 11 show the discretization by finite volume method applied to differential equations 1 and 2, respectively. Equations 12 and 13 are the discretizations of the Darcy model.

$$f_{1_{i,j}} = \frac{\left(\phi\rho_m V - \phi\rho_m V\Big|^{old}\right)_{i,j}}{\Delta t} + \left(\begin{array}{c}\left(\rho_o v_{o,r} A_r\Big|_{i+\frac{\Delta r}{2},j} - \rho_o v_{o,r} A_r\Big|_{i-\frac{\Delta r}{2},j}\right) + \left(\rho_w v_{w,r} A_r\Big|_{i+\frac{\Delta r}{2},j} - \rho_w v_{w,r} A_r\Big|_{i-\frac{\Delta r}{2},j}\right) \\ \left(\rho_o v_{o,z} A_z\Big|_{i,j+\frac{\Delta z}{2}} - \rho_o v_{o,z} A_z\Big|_{i,j-\frac{\Delta z}{2}}\right) + \left(\rho_w v_{w,z} A_z\Big|_{i,j+\frac{\Delta z}{2}} - \rho_w v_{w,z} A_z\Big|_{i,j-\frac{\Delta z}{2}}\right)\end{array}\right) = 0 \tag{10}$$

$$f_{2_{i,j}} = \frac{\left(\phi\alpha_o\rho_o V - \phi\alpha_o\rho_o V\Big|^{old}\right)_{i,j}}{\Delta t} + \left(\begin{array}{c}\left(\rho_o v_{o,r} A_r\Big|_{i+\frac{\Delta r}{2},j} - \rho_o v_{o,r} A_r\Big|_{i-\frac{\Delta r}{2},j}\right) \\ \left(\rho_o v_{o,z} A_z\Big|_{i,j+\frac{\Delta z}{2}} - \rho_o v_{o,z} A_z\Big|_{i,j-\frac{\Delta z}{2}}\right)\end{array}\right) = 0 \tag{11}$$

$$v_{f/o,r} = -\left(\frac{K_{i,j}.kr_{f/o}}{\mu_{f/o}}\right)\left[\frac{\Phi_{i,j} - \Phi_{i-1,j}}{\Delta r_{i,j}/2 + \Delta r_{i-1,j}/2}\right] \tag{12}$$

$$v_{f/o,z} = -\left(\frac{K_{i,j}.kr_{f/o}}{\mu_{f/o}}\right)\left[\frac{\Phi_{i,j}-\Phi_{i,j-1}}{\Delta z_{i,j}/2+\Delta z_{i,j-1}/2}\right] \tag{13}$$

The solution of the equations is accomplished using methods to solve nonlinear systems, such as Newton's method. Where, using equations residue 10 and 11, the Jacobian matrix is generated. Jacobian matrix permits to solve implicitly the primary variables, pressure and oil saturation, and also presents five-diagonal form because differential equations as a function of radial and axial spatial dimensions. Equation 14 illustrates the format obtained by the linear system after the completion of all procedures required by Newton's method.

4. RESULTS

The results are presented below and illustrate the numerical simulation validation for multi-layers case, the influence of filter cake, reservoir permeabilities and oil reservoir compressibility on drilling fluid filtrate profile. Table 1 illustrates the database used in the simulations.

Table 1 - Database used in numerical simulations

Variable	Values	Units
k_{mp}	2,5 x 10^{-12}	m^2
k_{cake}	2,0 x 10^{-17}	m^2
μ_f	2,5 x 10^{-03}	Pa.s
μ_o	3,3 x 10^{-02}	Pa.s
r_{well}	2,16 x 10^{-01}	m
ϕ_{mp}	3,50 x 10^{-01}	-
ϕ_{cake}	4,8 x 10^{-01}	-
C_s	8,0 x 10^{-02}	
ΔP	600	psi
time	12	hours

Figures 2 and 3 illustrate the numerical simulation validation. Figure 2 shows the pressure and saturation profile for the single layer case. The porous medium simulated had 20 meters of thickness and permeability of 2.5 x 10^{-12} m^2 (2500 mD). Figure 3 represents the same profiles (pressure and saturation) for a multi-layers porous medium. In this case, the results were simulated for two porous media with 10 m thickness each and a permeability of 2.5 x 10^{-12} m^2. The results are identical, ie, when the multi-layers case is running with the same permeabilities the results converge to single layers case.

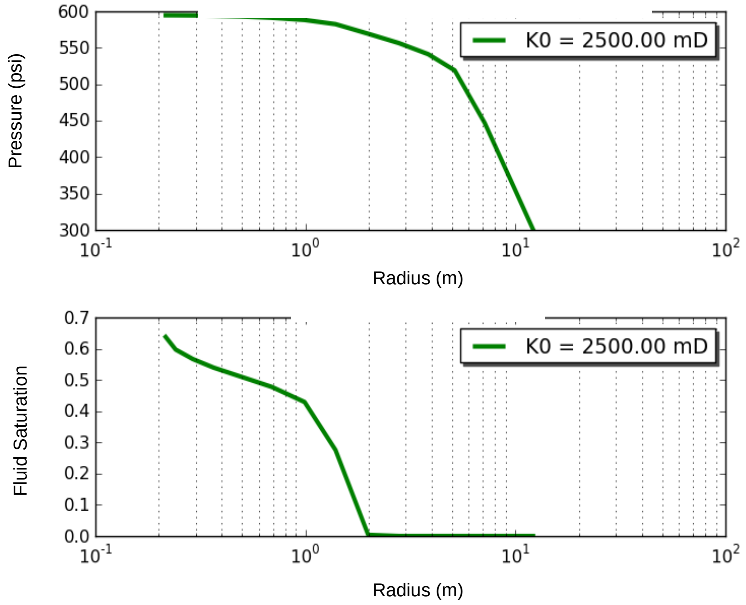

Figure 2. Numerical validation – Single layer case

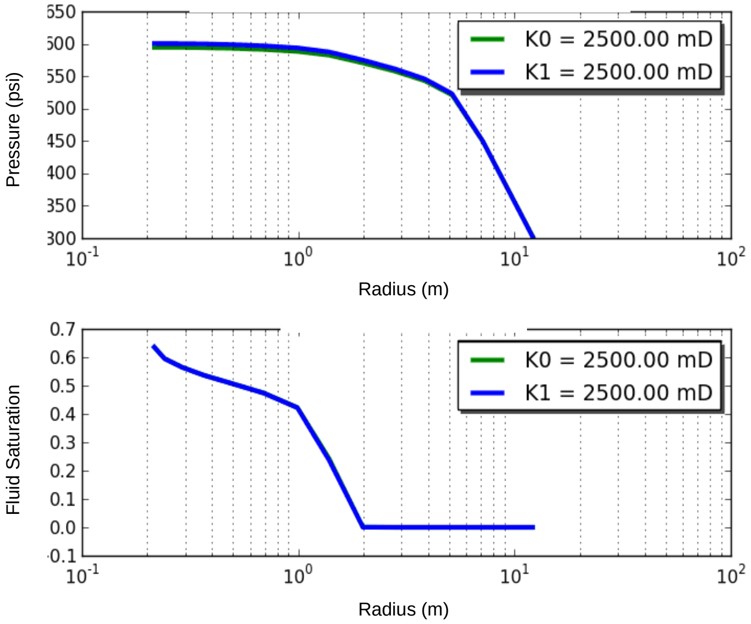

Figure 3. Numerical validation – Multi-layers Case

Figure 4 represents the 3D saturation profile. In this chart, it is possible to observe the filtrate saturation evolution along the time and radius. In this particular example, the filtrate invasion depth did not exceeded 2 meters.

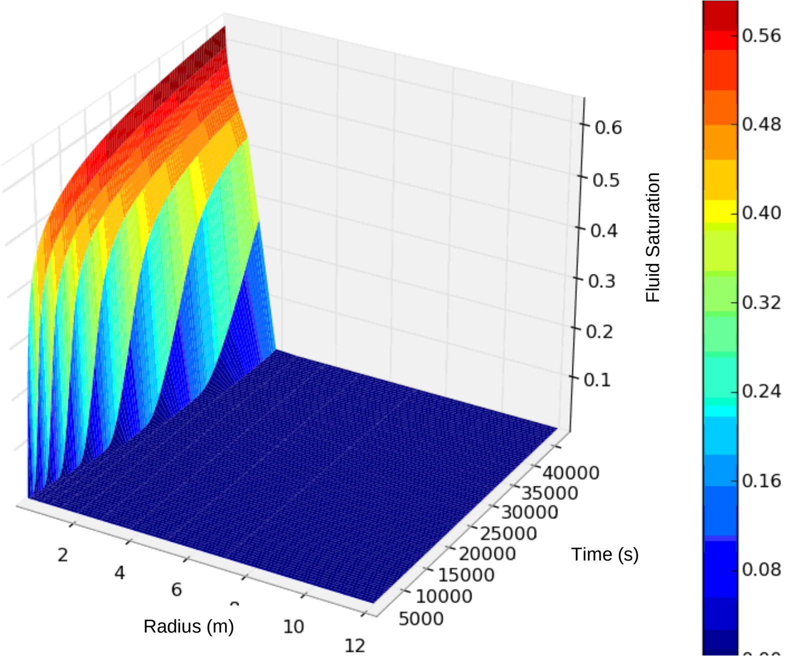

Figure 4.Saturation profile

4.1. Filter cake and reservoir permeabilities impact

Figures 5, 6, 7 and 8 illustrate the filter cake and reservoir permeabilities influence on pressure and saturation profile in the reservoir saturated with incompressible oil.

The results shown in Figure 5 were simulated considering - a reservoir permeability (first layer) of 2.5 x 10^{-13} m^2 (250 mD), filter cake permeability of 2.0 x 10^{-12} m^2 and a second reservoir layer with permeability of 2.0 x 10^{-12} m^2 (2000 mD). Pressure variation profile for each porous medium presents little change once the permeabilities are relatively high and the difference between them is only one order of magnitude. Physically, the results show good agreement since the higher filtrate saturation is observed in the porous medium of higher permeability. For example, for a reservoir radius of 0.3 meters, the filtrate saturation on first reservoir layer (250 mD) and second reservoir layer (2000 mD), respectively, are of 4% and 55%.

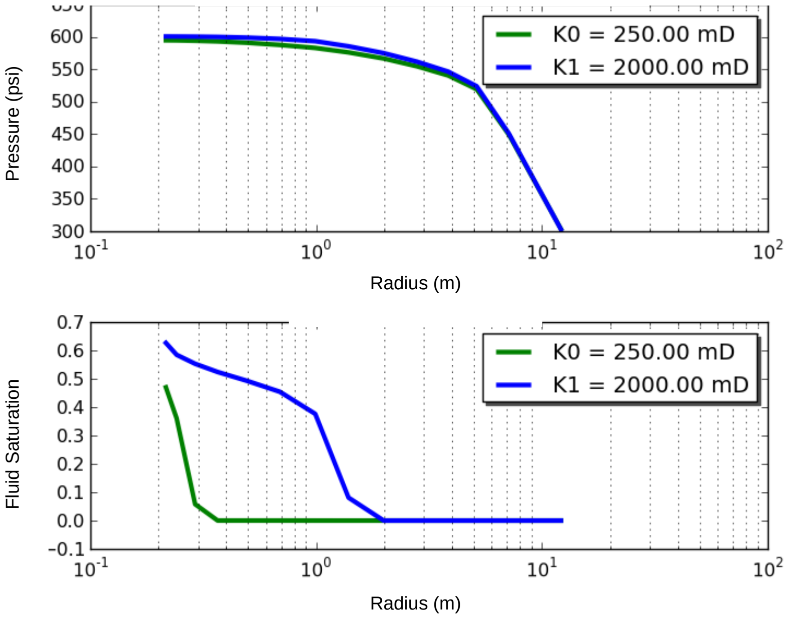

Figure 5. Saturation and pressure profile.

Results shown in Figure 6 illustrate the saturation and pressure profile for three different porous media, but with the same database as illustrated in Table 1. The results present the same physical coherence to the previously described and detailed in Figure 5. Figures 7 and 8 illustrate the 3D saturation profile for reservoir permeabilities of 950 mD and 2500 mD. The results indicate the higher filtrate invasion front is observed in the more permeable reservoir layer.

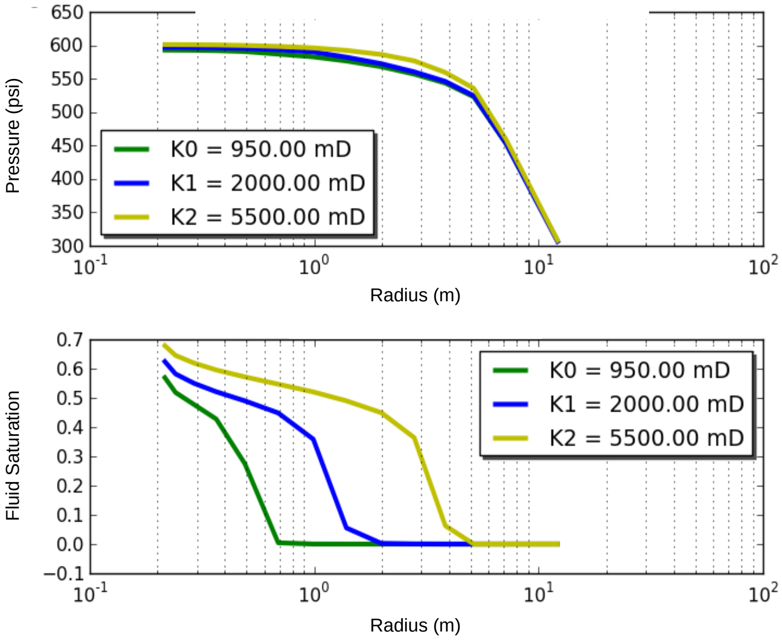

Figure 6.Saturation and pressure profile.

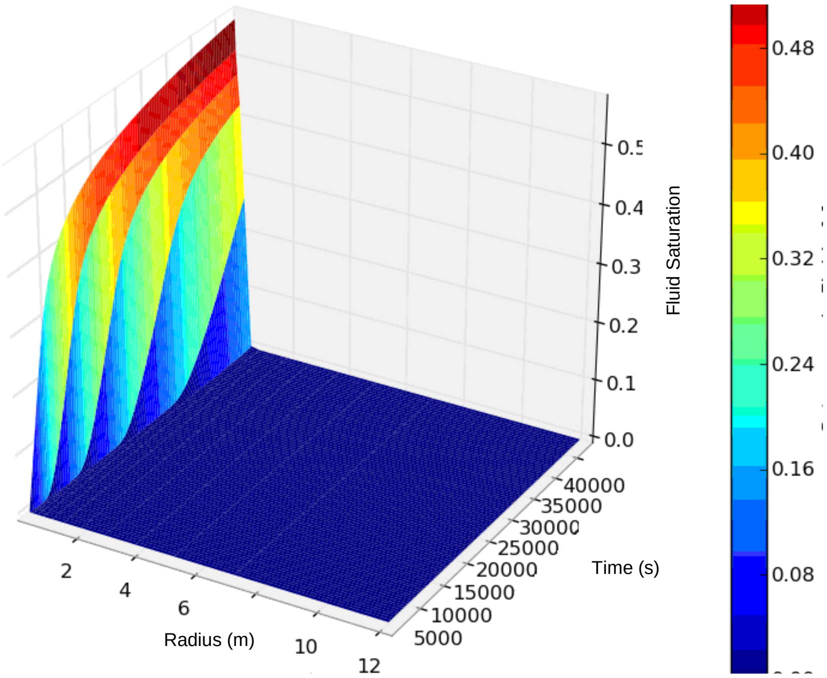

Figure 7. Saturation profile – 950 mD.

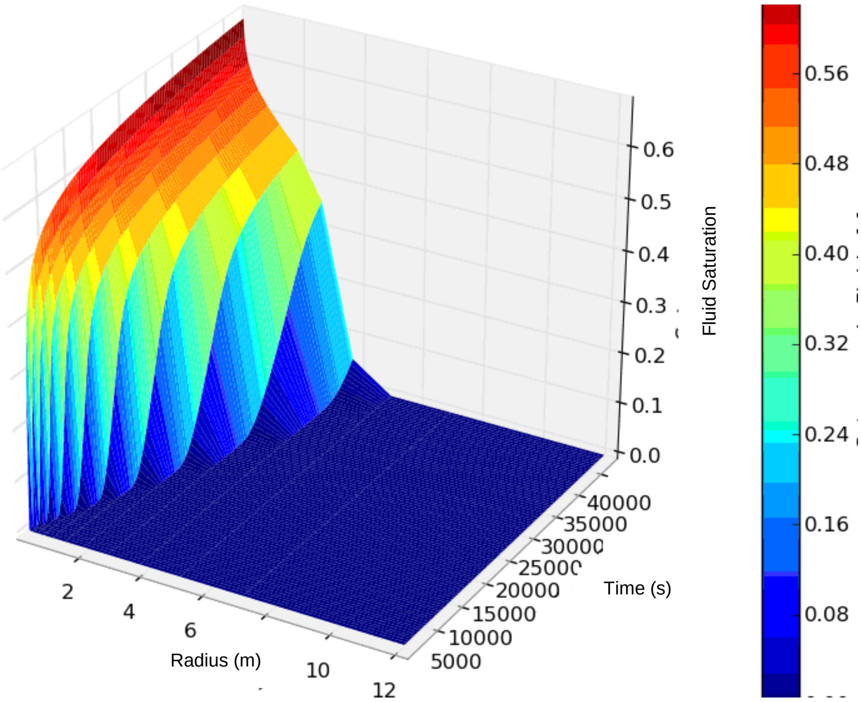

Figure 8. Saturation profile – 5500 mD.

Figures 9 and 10 show the impact of filter cake permeability on pressure and saturation profile. The simulations were performed considering filter cakes permeabilities of 2.0 x 10^{-16} m^2 and 2.0 x 10^{-17} m^2, respectively. The results indicate that the pressure profile is significantly affected by additional friction loss generated by the filter cake. The results indicate that the pressure profile is significantly affected by additional friction loss generated by the filter cake. Lower permeability values present a higher friction losses and consequently lower pressure values, at a given point of the reservoir. The saturation profile also can be observed, filter cake permeability low values will result lower saturation profiles. For example, for a reservoir radius of 0.3 meters, the filtrate saturation value is of 55% for filter cake permeability of 2.0 x 10^{-16} m^2. Filter cake permeability of 2.0 x 10^{-17} m^2, the filtrate saturation is 49%, approximately.

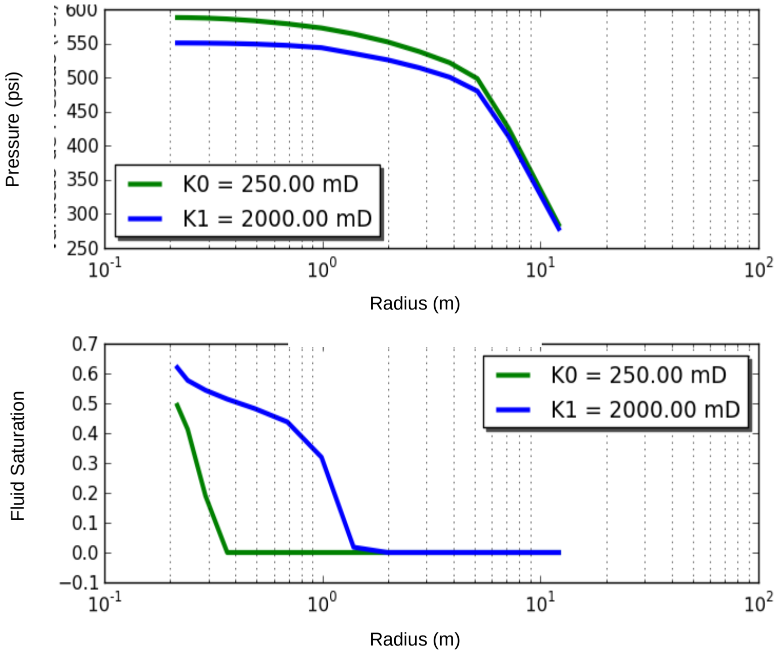

Figure 9. Pressure profile - $K_{\text{filter cake}} = 2{,}0 \times 10^{-16}\ m^2$

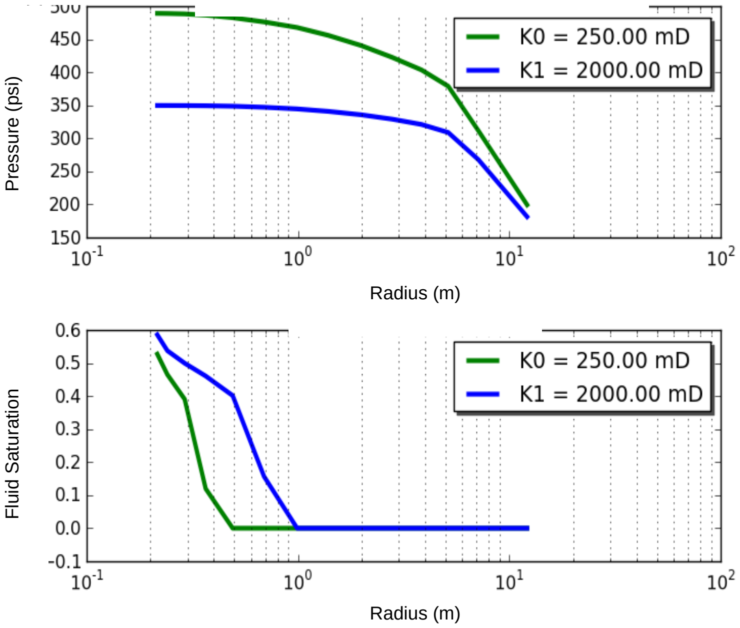

Figure 10. Pressure profile - $K_{\text{filter cake}} = 2{,}0 \times 10^{-17}\ m^2$.

4.2. Influence of oil compressibility on pressure and filtrate saturation profile

For the simulations considering compressible oil, the same behavior was observed, ie, the additional friction loss generated by filter cake permeability changes the pressure profile in the reservoir and consequently the saturation profile. Moreover, oil compressibility increases the filtrate saturation profile. Oil compressibility was determined analyzing a typical PVT oil chart from Campos's basin.

PVT analysis provides fluid properties such as formation volume factor, compressibility, viscosity, solubility ratio and saturation pressure. To determine the bubble point of a reservoir fluid, a sub-surface oil is loaded at constant pressure into the PVT cell, placed in equilibrium at reservoir temperature and reservoir pressure. This way, the volumetric behavior as a function of pressure during the tests is observed. From the bubble pressure and consequently the gas release, is possible to obtain values for the solubility ratio, formation volume factor and oil compressibility (Rutledge and Rajagopal, 2007). Oil density profile was determined using the following equation (Ahmed, 2002).

$$\rho_o = \rho_{Pref} \cdot e^{\left(C_o \cdot \left(P - P_{ref}\right)\right)} \tag{15}$$

Where ρ_o and C_o are oil density and oil compressibility, respectively, ρ_{ref} is the density at a reference pressure and P is the reservoir pressure.

Figures 11 and 12 show the filtrate saturation profile for two different oil compressibility values. Results indicate that high oil compressibility values will present high volume fraction (filtrate) at a given point in the reservoir. The results were obtained for filter cake permeability equal to 2.0 x 10^{-17} m^2, a reservoir radius of 100 meters and a simulation time of 12 hours. Additional data necessary for simulation are listed in Table 1.

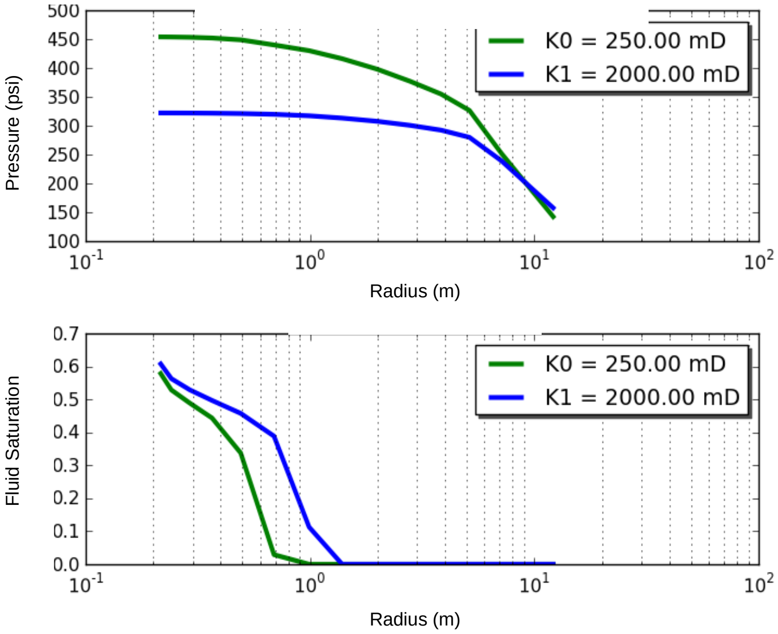

Figure 11. Saturation profile – Co = 8,0 x 10^{-6} psi^{-1}

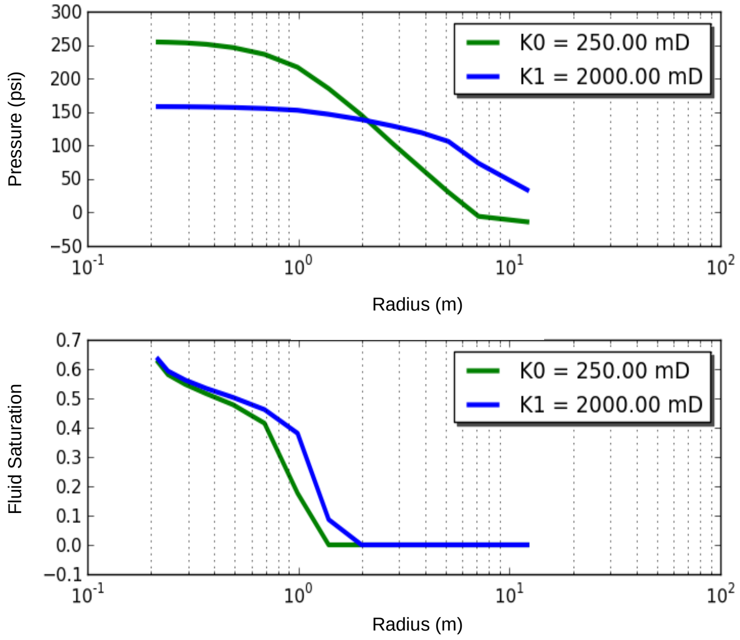

Figure 12. Saturation profile – Co = 8,0 x 10^{-4} psi^{-1}

The results indicate that for the same radius inside the reservoir, the filtrate saturation will be higher when the oil is more compressible. Simulated values with the oil compressibility equal to 8.0 x 10^{-6} psi^{-1} and 8.0 x 10^{-4} psi^{-1} (Figures 11 and 12 - green curves) present filtrate saturations values equal to 42% and 50%, respectively.

In oil and gas reservoir scenarios, the drilling fluid design to provide low filter cake permeability is very important, once for the same operational conditions, the filtrate invasion front of these scenarios is more progressive.

Figure 13 shows the 3D saturation profile considering oil compressibility equals to 8.0 x 10^{-6} psi^{-1} and 8.0 x 10^{-4} psi^{-1}. The results show a significant change in the saturation profile for different compressibility simulated.

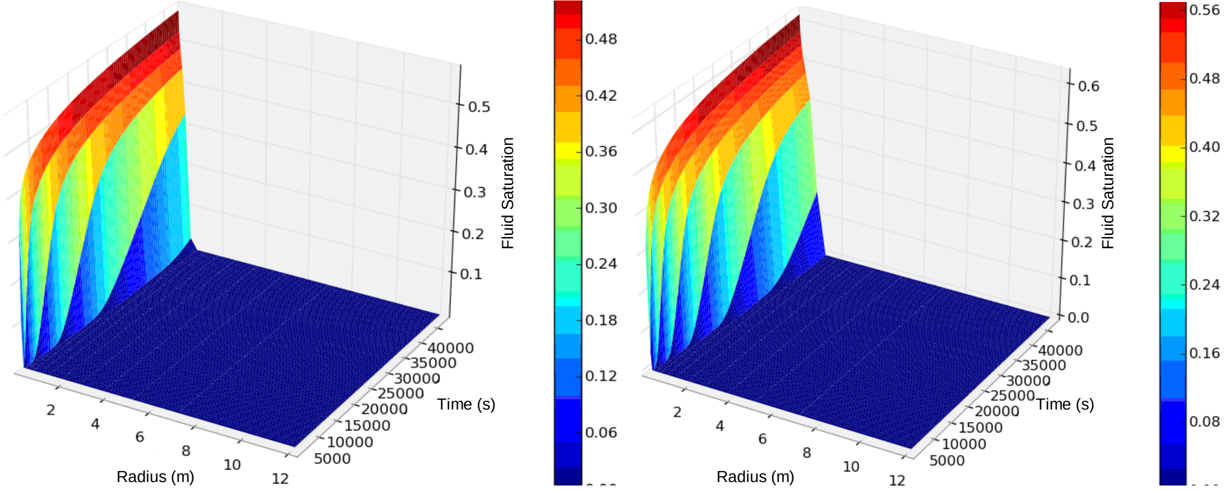

Figure 13. Saturation profile – Co = 8,0 x 10^{-6} psi^{-1} and Co = 8,0 x 10^{-4} psi^{-1} - 250 mD

5. FINAL REMARKS

Numerical simulation methodology presented in this work represents an useful tool for minimizing drilling fluid invasion into reservoir. Results show that it is possible to design drilling fluids properties to guarantee an invasion profile at acceptable levels for reservoir engineering, fluid engineering and geology requirements.

Numerical results indicate that filter cake permeability is the major factor governing invasion. Several efforts can be made regarding fluid composition in order to optimize this parameter. Solids size and shape can be a good path for that. Formation damage cause diagnosis is a major topic to be addressed and require the establishment of multidisciplinary teams involving: well testing, log interpretation and drilling experts.

Oil compressibility is the variable that changes the filtrate saturation profile into reservoir. This way, the consideration of these effects using data obtained by PVT analysis is very important to predict the invasion profile correctly. Some topics will be addressed in future to guarantee a more comprehensive modeling: filter cake compressibility, fine migration and internal filter cake, inclusion of shear stress in the cake filtration (dynamic filtration approach), imbibition effects (scenarios from gas reservoir and water blocking topics), reservoir anisotropy, non Darcy flows (gas reservoirs), heat transfer, comparison between numerical results and data obtained by: log data processing and sampling data interpretation

6. NOMENCLATURE

A = Area, m^2
C = Concentration, m^3/m^3
L = Length, in or cm
k = Permeability, mD ou m^2
kr = Relative Permeability,
P = Pressure, Pa
t = Time, s
V = Volume, m^3
v = Velocity, m/s

Greek letters
α = Saturation
ϕ = Porosity
ρ = Density, kg/m3
μ = Viscosity, Pa.s

Subscripts
cake = filter cake
f = filtrate
int = internal (well)
ext = external (reservoir)
o = oil
ref = reference
m = mixture
pm = porous medium
s = solid
w = water

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