MODELING NON NEWTONIAN FLUID INVASION INTO RESERVOIR ROCKS

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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. Unreliable sampling may lead to wrong reservoir evaluation and, in critical cases, to wrong decisions concerning reservoir exploitability.
Besides, drilling fluid invasion may also provoke irreversible reservoir damage, reducing its initial and /or its long term productivity (Ladva et al., 2000). Such problem can be critical in heavy oil reservoirs, where oil and filtrate interaction can generate stable emulsions. Invasion in light oil reservoir 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.
A common practice in the industry is the addition of bridging agents, such as calcium carbonates in the drilling fluid composition. Such products would form a low permeability layer at the well walls which would control invasion. An adequate drilling fluid design requires bridging agent size distribution and concentration optimization. The ability of the fluid system to prevent invasion is normally evaluated by standardized static filtration experiments. In these tests, the fluid is pressurized through a filter paper or into a consolidated inert porous medium. The volume which crosses the porous core is monitored along the time.
This article presents the Darcy flow modeling of non-compressible cakes to reproduce adequately the filtration of a Non Newtonian fluid + particulate system through porous medium and non Newtonian radial flow modeling to predict the invasion profile into reservoir. Pressure differential, rheological behavior, filter cake permeability proved to be relevant parameters affecting the invasion profile.
***Keywords**: Drilling fluid invasion, Non-Newtonian radial flow modeling, Reservoir rocks*

1. INTRODUCTION

In petroleum engineering, well drilling is an area of continuous development in order to improve the current technologies and look for new ones which can be applied to the adverse conditions faced nowadays and enable operations that were only conceptual some decades ago. Oil well drilling involves costly operations where avoiding reservoir damage and minimizing operational time are very important issues. The drilling operation generally occurs through weight and rotation of a string which extremity is connected to a bit. Simultaneously, a drilling fluid is circulated through the well according to the following path: the fluid is injected into the column, passes through the bit nozzles and returns through the annular space formed by the wellbore and drilling column. Figure 1 highlights the fluid circulation scheme.

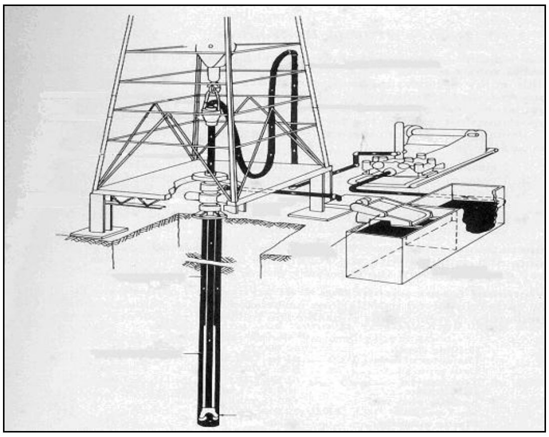


Figure 1 - Fluid circulation system

Different types of fluid are used in the several the drilling phases of an offshore well. In its initial phases, the well is drilled without fluid return, with sea water or water with clay when higher densities are required. Extended and high angle sections are normally drilled with fluids based on synthetic oils with good lubricity and low reactivity with shales. Reservoir rocks are drilled with a fluid family known as drill-in, composed by saline polymeric solutions with bridging agents.

One of the drilling fluid basic functions is to exert hydrostatic pressure over the permeable formations to avoid the formation fluid invasion to the well while the drilling operation takes place. The fluid pressure is normally kept above the formation pore pressure to prevent from kick events (formation fluid invasion to the well), that, in some cases, can lead to an uncontrolled influx (blowout). This concept, called overbalanced drilling, is traditionally employed in most of the drilling operations worldwide and in Brazil.

As the bit penetrates the reservoir rock, the drilling fluid invades the formation due to the positive pressure differential between the well and the reservoir rock. Portions of the liquid phase of the drilling fluid are lost to the adjacent formation while part of the solids presented in drilling fluid, constituted by particles smaller than the formation pore size, penetrate the rock during the fluid loss period, rapidly plugging the region around the well (Martins, 2004). Larger particles accumulate on the wellbore walls, initiating an external cake formation. The filtrate and solid particles invasion during this process cause damage to formation around the well.

The main purpose this paper is to describe a mathematical formulation which allows the estimation of filter cake permeability and non Newtonian invasion profile into the reservoir rock. The final goal is to couple experimental filter cake permeability data obtained from linear flow tests and radial flow modeling to optimize drilling fluid designed.

2. FUNDAMENTALS

Consider a static filtration experiment, where a fluid, when submitted to constant differential pressure, flows through a porous medium previously saturated with the same fluid. The fluid volume that passes over the porous medium is monitored through the time and its rheological properties evaluated at the test temperature. Figure 2 shows the experimental scheme.

Figure 2 shows the experimental scheme

The fluid flow through to the porous media is normally describes by Darcy (1856):

$$\frac{\mu_{ef}}{k}\left[1 + c\frac{\sqrt{k}\,\left|\vec{q}\right|\rho_f}{\mu_{ef}}\right]\left|\vec{q}\right| = -\left(\nabla p - \rho_f\,\vec{g}\right) \tag{1}$$

Where the k is the porous medium permeability, μ_{ef} is the fluid viscosity, c is the Forchheimer (1901) constant and Re is the Reynolds number that can be describes by:

$$\mathrm{Re} = \frac{\sqrt{k}\left|\vec{q}\right|\rho_f}{\mu_{ef}} \tag{2}$$

and q is the superficial velocity that can be defined by:

$$\left|\vec{q}\right| = \vec{v}\varepsilon \tag{3}$$

When the fluid flow is very slow i.e

$$\mathrm{Re} << 1 \tag{4}$$

Quadratic expression given by Eq. (1) can be approximated by:

$$\frac{\mu_f}{k}\left|\vec{q}\right| = -\left(\nabla p - \rho_f \vec{g}\right) \tag{5}$$

3. LINEAR UNIDIRECIONAL FLOW MODELING (LAB CONFIGURATION)

During the reservoir rock drilling is normally used a drilling fluid type known as drill-in fluids. These fluids are composed by an aqueous base (normally brine) with calcium carbonate (adding different particle size distribution) and polymer additives that determine non-Newtonian behavior. Calcium carbonate and polymer additives help to form a low permeability filter cake and minimize drill in fluid invasion into reservoir.

A filtrate sample was collected and taken as an example for the rheological characterization using a RS 600 Haake rheometer, using cone plate geometry. Figure 3 shows the flow curve and the power law approach to drill in fluid filtrate.

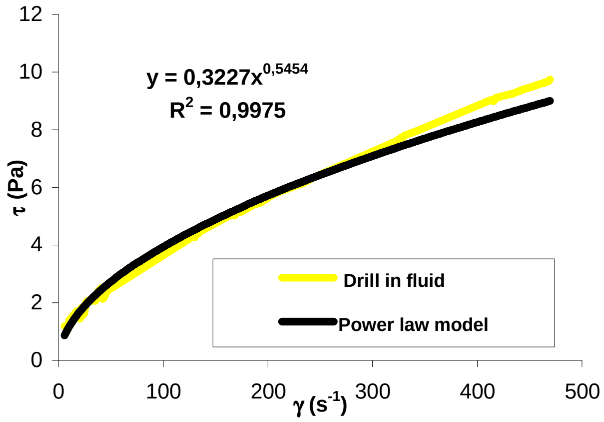


Figure 3 - Drill in fluid rheological behavior

Figure 3 shows the power law approach with correlation coefficient (R^2) approximately equal to 1. Consistency index (M) and behavior index (n), respectively values equal to 0.3227 ($Pa.s^n$) and 0.54, characterizing the non-Newtonian behavior of the filtrate sample evaluated.

To obtain a model able of predicting the filter cake properties, monitoring the filtration parameters, were considered the following assumptions:

- Filter cake thickness is defined by the solids concentration in the fluid and invasion volume.
- Filter cake permeability is constant.
- Hydrostatic effects are negligible.
- Fluid filtrate presents Power Law behavior.
- There is no solids invasion into the porous medium.

Non Newtonian linear modeling: Integrating the Eq. (5) along the filter cake and porous medium, considering incompressible filter cake and neglecting the hydrostatic effects:

$$\Delta p = \mu_{ef} \cdot \vec{q} \cdot \left[\frac{h_{pm}}{k_{pm}} + \frac{h_{cake}(t)}{k_{cake}}\right] \tag{6}$$

Filtrate viscosity of a non Newtonian fluid can be estimated by a Power Law approach:

$$\mu_{ef} = M.\gamma^{n-1} \tag{7}$$

The shear rate in the porous medium can be estimated, according to Massarani (1999), as a function of the superficial velocity (q):

$$\gamma = \frac{\vec{q}}{\sqrt{K_{pm}}} \tag{8}$$

Inserting the Eq. (8) in the Eq. (7):

$$\mu_{ef} = M.\left(\frac{\vec{q}}{\sqrt{K_{pm}}}\right)^{n-1} \tag{9}$$

Inserting the Eq. (9) in the Eq. (6):

$$\Delta p = M.\left(\frac{\vec{q}}{\sqrt{K_{pm}}}\right)^{n-1}.\vec{q}.\left[\frac{h_{pm}}{k_{pm}}+\frac{h_{cake}(t)}{k_{cake}}\right] \tag{10}$$

Rearranging the Eq. (10):

$$\Delta p = M.\left(\frac{\vec{q}}{\sqrt{K_{pm}}}\right)^{n}.\sqrt{K_{pm}}.\left[\frac{h_{pm}}{k_{pm}}+\frac{h_{cake}(t)}{k_{cake}}\right] \tag{11}$$

$$(\Delta p)^{\frac{1}{n}} = M^{\frac{1}{n}}.\left(\frac{\vec{q}}{\sqrt{K_{pm}}}\right).\sqrt{K_{pm}}^{\frac{1}{n}}.\left[\frac{h_{pm}}{k_{pm}}+\frac{h_{cake}(t)}{k_{cake}}\right]^{\frac{1}{n}} \tag{12}$$

$$\left(\frac{\Delta p}{M}\right)^{\frac{1}{n}}.\left(\frac{1}{K_{pm}}\right)^{\frac{1-n}{n}} = \vec{q}.\left[\frac{h_{pm}}{k_{pm}}+\frac{h_{cake}(t)}{k_{cake}}\right]^{\frac{1}{n}} \tag{13}$$

Where:

$$\vec{q} = \frac{Q}{A} = \frac{1}{A}\frac{dV_f}{dt} = -\frac{dh_{cake}}{dt} \tag{14}$$

Porosity is defined by:

$$\varepsilon_{pm} = \frac{V_p}{V_s+V_p} \tag{15}$$

Porous volume can be obtained by:

$$V_p = \frac{\varepsilon_{pm}.V_s}{(1-\varepsilon_{pm})} \tag{16}$$

Filter cake volume can be defined by:

$$A.h_{cake} = V_s + V_p \tag{17}$$

Substituting the Eq. (16) in the Eq. (17):

$$A.h_{cake} = V_s.\left(1+\frac{\varepsilon_{mp}}{1-\varepsilon mp}\right) \tag{18}$$

or

$$A.h_{cake} = V_s.\left(\frac{1}{1-\varepsilon_{pm}}\right) \tag{19}$$

Differentiating Eq. (19) in relation to time:

$$A.\frac{dh_{cake}}{dt} = \frac{dV_s}{dt}.\left(\frac{1}{1-\varepsilon_{pm}}\right) \tag{20}$$

Solids Concentration is now defined by:

$$C_s = \frac{V_s}{V_s + V_f} \tag{21}$$

$$V_f = \frac{V_s \cdot (1 - C_s)}{C_s} \tag{22}$$

or

$$V_s = \frac{V_f \cdot C_s}{(1 - C_s)} \tag{23}$$

Substituting the Eq. (23) in the Eq. (19):

$$h_{cake} = \frac{V_f.(C_s)}{A.(1-C_s)}.\left(\frac{1}{1-\varepsilon_{pm}}\right) \tag{24}$$

Substituting the Eq. (24) in the Eq. (13):

$$\left(\frac{\Delta P}{M}\right)^{\frac{1}{n}}.\left(\frac{1}{\sqrt{K_{pm}}}\right)^{\frac{1-n}{n}}.A.dt = \left[\frac{h_{pm}}{K_{mp}}+\frac{V_f}{A.k_{cake}}.\left(\frac{1}{1-\varepsilon_{pm}}\right).\left(\frac{C_s}{1-C_s}\right)\right]^{\frac{1}{n}}.dV_f \tag{25}$$

Defining:

$$a = \frac{h_{mp}}{K_{mp}} \tag{26}$$

$$b = \left[\frac{1}{A}.\left(\frac{1}{1-\varepsilon}\right).\left(\frac{C_s}{1-C_s}\right)\right] \tag{27}$$

$$\left(\frac{\Delta p}{M}\right)^{\frac{1}{n}}.\left(\frac{1}{\sqrt{K_{mp}}}\right)^{\frac{1-n}{n}}.Adt = M^{\frac{1}{n}}.\left(\frac{\vec{q}}{\sqrt{K_{mp}}}\right).\sqrt{K_{mp}}^{\frac{1}{n}}.\left[a+\frac{V_f}{k_{torta}}b\right]^{\frac{1}{n}}.dV_f \tag{28}$$

Integrating the Eq. (28) and applying the initial condition (V_f =0 em t =0) in the Eq. (28), resulting in C = 0.

$$t = \left[\frac{n.(a.K_{mp}+b.V_f)}{b.(n+1)}\right]\left[a+\frac{V_f}{k_{torta}}b\right]^{\frac{1}{n}}.\left(\frac{M}{\Delta P}\right)^{\frac{1}{n}}.\left(\sqrt{K_{mp}}\right)^{\frac{1-n}{n}}.\frac{1}{A} \tag{29}$$

Equation (29) (presented by Andrade et. al, 2007) takes to the Newtonian linear model presented by Waldmann et. al. (2004), when:

- n = 1 (behavior index)
- M = μ_{ef} (consistency index equal to viscosity)

3.1 Linear Unidirecional Flow Validation

To evaluate the flow through consolidated porous media, a commercial equipment (FANN - High Pressure High Temperature Press Filter Series 387) was used. In this test, a fixed volume of fluid is set over a synthetic porous medium saturated with the same fluid and submitted to a pre-established pressure differential. The saturation procedure consists in the immersion of the porous medium into the fluid under vacuum conditions. After the saturation stage, the porous medium is placed into the press filter leaned on a high permeability screen in order to minimize the pressure losses in the equipment outlet. Figure 4 shows the experimental cell. Ceramic disks (6,35 cm diameter and 0,635 cm thickness) were used as the filtration media.

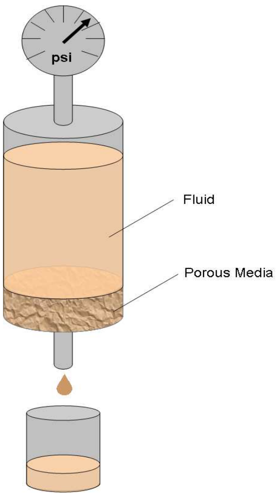


Figure 4 - The experimental cell

Figure 5 shows the comparison between predict and experimental values. The tests were carried out under a 500 psi differential pressure, porous medium permeability and porosity are respectively, $1x10^{-15}m^2$ and 0,17, filter cake permeability estimated by non Newtonian linear model equal to $3x10^{-18}m^2$, filter cake porosity and solids concentration are respectively 0,48 and 8%.

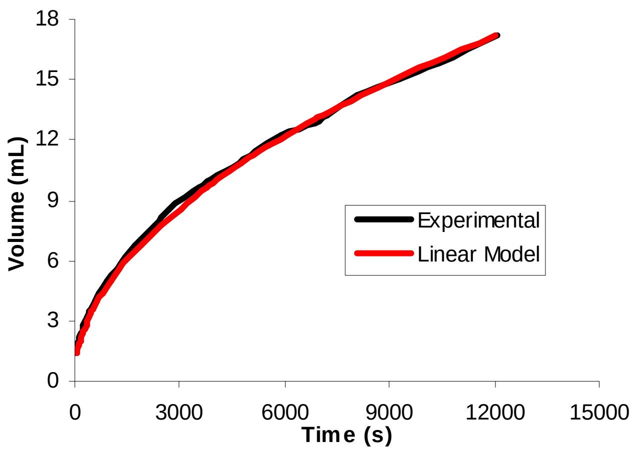


Figure 5 – Filtrate volume vs time curve

The main purpose of the linear static modeling is to provide a mathematical tool which allows to estimate the filter cake permeability. The determination of this parameter is very important to the radial flow modeling, because with this information it is possible to predict invasion profile in the reservoir and then to optimize drilling fluid properties to guarantee acceptable levels of invasion into reservoir.

4. NON NEWTONIAN RADIAL FLOW MODELING (WELL CONFIGURATION)

Adopting the same filter cake building hypothesis detailed for the linear flow, the following expression relates invasion radius and time. This equation is valid for a reservoir saturated with a Newtonian fluid and when the filtrate has low mobility, i.e., it does not percolate through the reservoir fluid.

Radial Friction losses to Newtonian fluid can be calculated by:

$$-\frac{dp}{dr}=\frac{\mu_{ef}\cdot Q}{K_{pm}\cdot A_{pm}}+\frac{\mu_{ef}\cdot Q}{K_{fc}\cdot A_{fc}}+\frac{\mu_0\cdot Q}{K_{pm}\cdot A_{pm}} \tag{30}$$

and for Non Newtonian fluid can be calculated by (changing μ_{ef} by Eq. 9):

$$-\frac{dp}{dr}=\frac{M\cdot Q^n}{K^{\frac{n+1}{2}}{}_{pm}\cdot A^n{}_{pm}}+\frac{M\cdot Q^n}{K^{\frac{n+1}{2}}{}_{fc}\cdot A^n{}_{fc}}+\frac{\mu_0\cdot Q}{K_{pm}\cdot A_{pm}} \tag{31}$$

Integrating:

$$-\int_{Pwell}^{\Pr es}dp=\frac{M\cdot Q^n}{K^{\frac{n+1}{2}}{}_{pm}\cdot(2\pi L)^n}\left[\int_{R\text{int}}^{Rinv}\frac{1}{r^n}dr+\frac{K^{\frac{n+1}{2}}{}_{pm}}{K^{\frac{n+1}{2}}{}_{fc}}\int_{Rfc}^{R\text{int}}\frac{1}{r^n}dr+\frac{Q\cdot\mu_{ef}}{2\pi L\cdot K_{pm}}\int_{Rinv}^{\text{Re}xt}\frac{1}{r}dr\right] \tag{32}$$

$$\Delta P=\frac{\mu_{ef}\cdot Q}{K_{pm}\cdot 2\pi L}\ln\frac{R_{ext}}{R_{inv}}+\frac{M\cdot Q^n}{K^{\frac{n+1}{2}}{}_{pm}\cdot(2\pi L)^n}\cdot\left[\left(\frac{R_{inv}{}^{1-n}-R_{\text{int}}{}^{1-n}}{1-n}\right)+\frac{K^{\frac{n+1}{2}}{}_{pm}}{K^{\frac{n+1}{2}}{}_{fc}}\cdot\left(\frac{R_{\text{int}}{}^{1-n}-R_{fc}{}^{1-n}}{1-n}\right)\right] \tag{33}$$

Solids Concentration is now defined by:

$$C_s=\frac{V_s}{V_s+V_{inv}} \tag{34}$$

$$C_s\cdot V_{inv}=V_s\cdot(1-C_s) \tag{35}$$

Invaded Volume can be calculated by:

$$V_{inv}=\frac{V_s\cdot(1-C_s)}{C_s} \tag{36}$$

$$V_s=\pi\cdot\left(R^2{}_{inv}-R^2{}_{fc}\right)\cdot L\cdot\phi_{pm}\cdot(1-S_{or}-S_{iw})\cdot\frac{C_s}{1-C_s} \tag{37}$$

And:

$$V_s=\pi\cdot\left(R^2{}_{\text{int}}-R^2{}_{fc}\right)\cdot L\cdot(1-\phi_{fc}) \tag{38}$$

Equaling Eq. (37) and Eq. (38):

$$R_{fc}=\sqrt{\frac{\beta\cdot R^2{}_{\text{int}}-R^2{}_{inv}\cdot\chi}{\beta-\chi}} \tag{39}$$

Where:

$$\beta=\phi_{mp}\cdot(1-S_{or}-S_{iw})\cdot\frac{C_s}{1-C_s}\quad\text{and}\quad\chi=(1-\phi_{fc}) \tag{40}$$

Defining flow rate as:

$$Q=\frac{dV_{inv}}{dt} \tag{41}$$

Substituting Eq. (37) in Eq. (36):

$$V_{inv}=\pi\cdot\left(R^2{}_{inv}-R^2{}_{\text{int}}\right)\cdot L\cdot\phi_{pm}\cdot(1-S_{or}-S_{iw}) \tag{42}$$

Differentiating in relation to time:

$$Q=\frac{dV_{inv}}{dt}=\phi_{pm}\cdot\left(1-S_{or}-S_{iw}\right)\cdot L\cdot 2\pi\cdot R_{inv}\cdot\frac{dR_{inv}}{dt} \tag{43}$$

Substituting Eq. (43) in Eq. (33):

$$\Delta P=\frac{\mu_{ef}\cdot\phi_{pm}\cdot\left(1-S_{or}-S_{iw}\right)}{K_{pm}}R_{inv}\cdot\frac{dR_{inv}}{dt}+\frac{M\cdot\left(\phi_{pm}\cdot R_{inv}\cdot\left(1-S_{or}-S_{iw}\right)\right)^{n}}{K^{\frac{n+1}{2}}{}_{pm}}\left(\frac{dR_{inv}}{dt}\right)^{n}\cdot\left[\left(\frac{R_{inv}{}^{1-n}-R_{int}{}^{1-n}}{1-n}\right)+\frac{K^{\frac{n+1}{2}}{}_{pm}}{K^{\frac{n+1}{2}}{}_{fc}}\cdot\left(\frac{R_{int}{}^{1-n}-R_{fc}{}^{1-n}}{1-n}\right)\right] \tag{44}$$

Equation (44) was discretized using the Taylor series for the transient term, as the discrete equation (45) had no explicit solution was necessary to apply a method for the solution of non linear equation. The method used to solve the non linear discrete equation was the method of bisection for simplicity and security convergence.

$$\min_{R_{inv}^{n+1}}\left(\Delta P-\frac{\mu_{ef}\cdot\phi_{pm}\cdot\left(1-S_{or}-S_{iw}\right)}{K_{pm}}R_{inv}\cdot\frac{\left(R_{inv}^{n+1}-R_{inv}^{n}\right)}{\Delta t}+\frac{M\cdot\left(\phi_{pm}\cdot R_{inv}\cdot\left(1-S_{or}-S_{iw}\right)\right)^{n}}{K^{\frac{n+1}{2}}{}_{pm}}\left(\frac{\left(R_{inv}^{n+1}-R_{inv}^{n}\right)}{\Delta t}\right)^{n}\cdot\left[\left(\frac{R_{inv}^{1-n}-R_{int}^{1-n}}{1-n}\right)+\frac{K^{\frac{n+1}{2}}{}_{pm}}{K^{\frac{n+1}{2}}{}_{fc}}\cdot\left(\frac{R_{int}^{1-n}-R_{fc}^{1-n}}{1-n}\right)\right]\right)\cong 0 \tag{45}$$

4.1 Non Newtonian Radial Flow Modeling Validation

To validate the non Newtonian radial flow modeling of a fluid with rheological behavior that follows power law model will be used the same idea described in non-Newtonian linear modeling validation: adopting a behavior index (n) and consistency index (M) that tend respectively to 1 and the effective viscosity (μ_{ef}) it is expected that the invasion profile for both models are identical.

Figure 6 shows the invasion profile in three different curves: Newtonian radial analytical modeling (baby blue curve), Newtonian radial numerical modeling (gray curve) and non Newtonian radial modeling (red curve) when n and M tends to 1 and effective viscosity, respectively. The results showed in Figure 6 are identical, validating the numerical methodology and non Newtonian radial flow modeling.

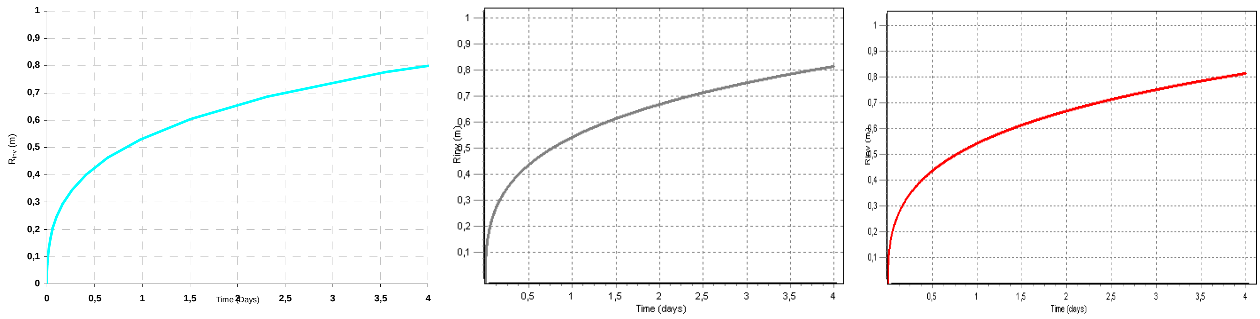


Figure 6 - Numerical methodology and non Newtonian radial flow modeling validation

4.2 Sensibility Analysis

- Pressure Differential; this is a major issue in well design: while large overbalances guarantee wellbore stability and control, it may enhance invasion. Figure 7 shows the influence of the pressure differential on the invasion radius for five different overbalance pressures.

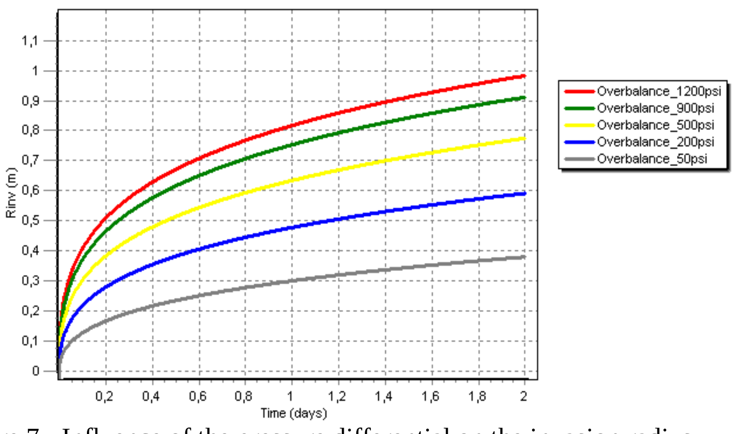
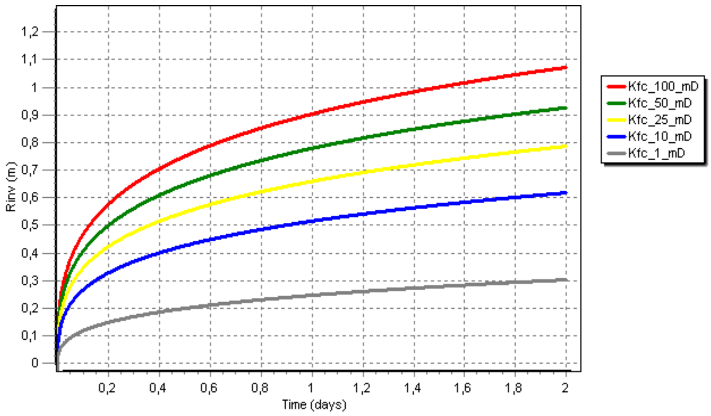
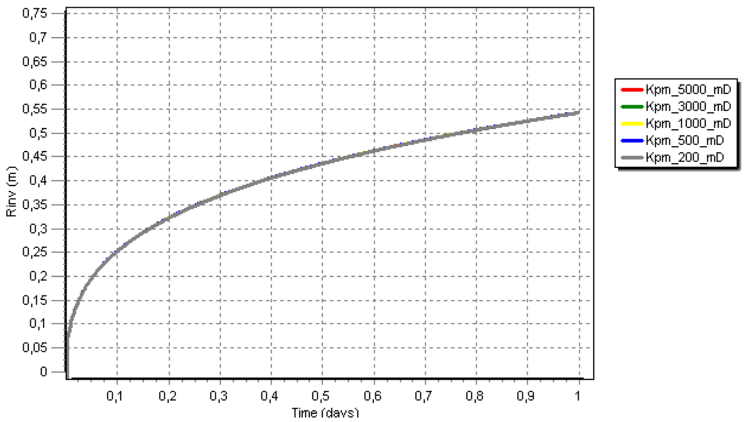


Figure 7 - Influence of the pressure differential on the invasion radius

- Filter cake and reservoir permeabilities; Figures 8 and 9 illustrate the effect of the filter cake and reservoir permeabilities on the invasion radius. Table 1 details the base data for the simulation. Results indicate that filter cake permeability plays the major role while reservoir permeability effects are negligible.



Figures 8 - Effect of the filter cake permeabilities on the invasion radius



Figures 9 - Effect of reservoir permeabilities on the invasion radius

Table 1 - Details the base data for the simulation

Description	Value	Unit
Porous medium permeability	7.50E-13	mD
Filter cake permeability	2.00E-17	mD
Filtrate viscosity	2.50E-03	Pa.s
Reservoir fluid viscosity	3.30E-02	Pa.s
Internal radius	2.16E-01	m
Reservoir porosity	3.50E-01	%
Solids concentration	8.00E-02	%
Consistency index	1.20	$Pa.s^n$
Behavior index	0.5	-
Differential pressure	300	Psi

- Filtrate rheological properties and reservoir fluid viscosities; Figures 10 and 11 illustrate the effect of the filtrate rheological properties (behavior index and consistency index, respectively). Results indicate when behavior and consistency index increase the invasion radius decreases, because the effective fluid viscosity is reduced (see Eq.7). Effective viscosity plays an important role due to the fact that it is the fluid which crosses the low permeability filter cake, generating the pressure losses which govern the system. Figure 12 shows the impact of reservoir fluid viscosities on the invasion radius. The same base data detailed on Table 1 are used. The model says, on the other hand, that oil viscosity has negligible effect on invasion. This conclusion is a lot influenced by the non-percolation hypothesis. On a real two fluid model, the viscosity ratio between both fluids should also play an important role in the process.

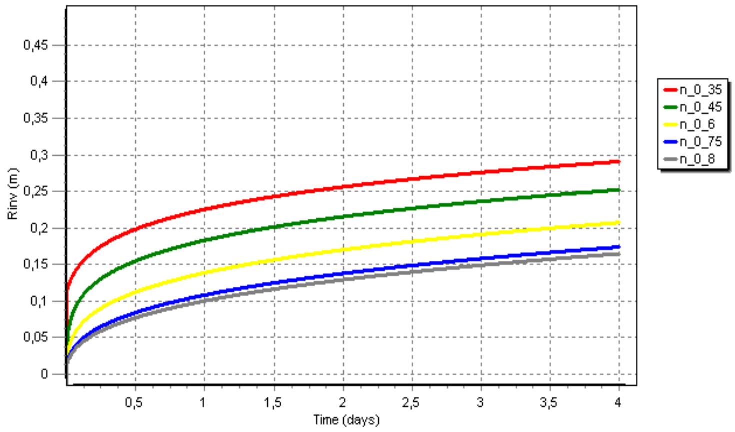


Figure 10 - Effect of the behavior index on the invasion radius

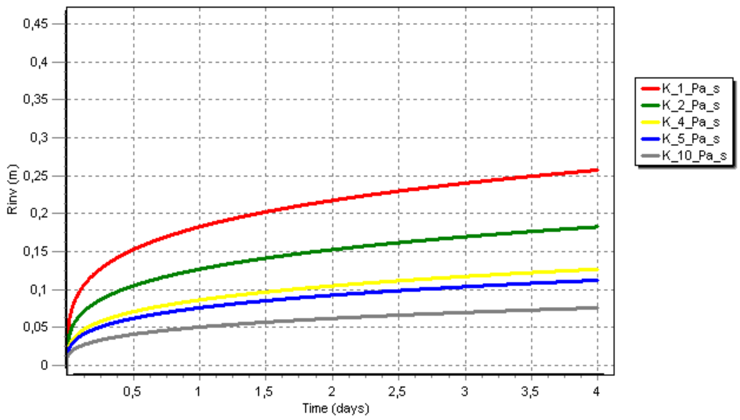


Figure 11 - Effect of the consistency index on the invasion radius

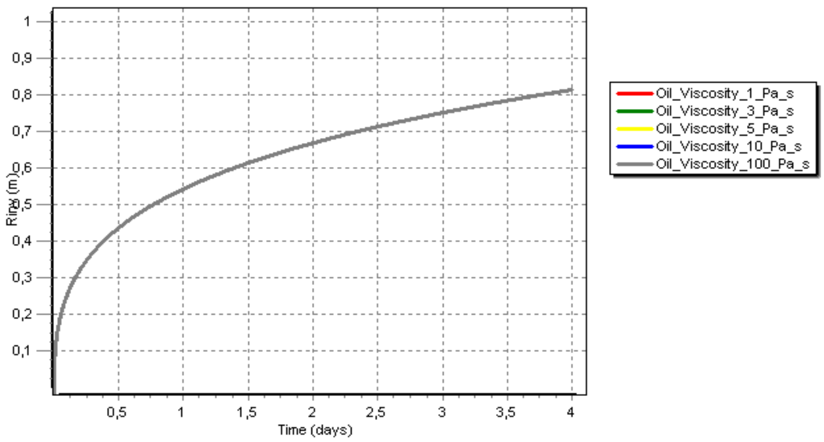


Figure 12 - Effect of the oil viscosity on the invasion radius

5. FINAL REMARKS

- Formation damage cause diagnosis is a major issue to be addressed and require the establishment of multidisciplinary teams involving well testing, log interpretation and drilling experts. A sensibility analysis on the linear Darcy flow of a cake building of Non Newtonian fluid through porous media indicates that filter cake permeability is a major parameter governing the process.

- Non Newtonian linear and radial flow modeling presented in this paper can be a powerful tool to optimize filtration parameters, filter cake properties, drill in fluids design and minimize drill in fluid invasion.

- The filtration properties design methodology proposed in this article is a powerful tool to link lab and field results. Of course the simplified flow models adopted here can be substituted by more realistic ones, including filter cake compressibility, filtrate – reservoir fluid percolation, reservoir anisotropy among other relevant items.

- Further steps in the study include the determination of optimum particle size distribution which minimizes filter cake permeability, modeling of compressible cake formation, reservoir anisotropy and testing real fluid systems. Model 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.

6. NOMENCLATURE

A = Area, cm^2
C = Concentration, cm^3/cm^3
c = Forchheimer constant
d = Diameter, in
g = Gravity, m/s^2
h = Thickness, in or cm
K = Permeability, mD
L = Length, cm
M = Consistency index, $Pa.s^n$
n = Beahavior index
P = Pressure, psi
q = Superficial velocity, cm/s
Q = Volumetric flow rate, cm^3/s
R = Radius, in or cm
S = Saturation
t = Time, s
V = Volume, cm^3

Greek letters

ϕ = Porosity
μ = Viscosity, cp
ρ = Density, ppg

Subscripts

ext = External index
fc = Filter cake index
int = Internal index
inv = Invasion index
iw = Irreducible water index
L = Liquid index
o = Formation fluid index
or = Residual oil index
p = Pore index
pm = Porous medium index
res = Reservoir index
s = Solids index

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