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NON-NEWTONIAN FLUID DISPLACEMENT IN ANNULAR SPACE

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Abstract. *The displacement of drilling mud by cement slurry in completion operations of oil and gas wells involves a time-dependent displacement of non-Newtonian fluids in concentric and eccentric annuli. The success of this operation guarantee the lifetime of the wells. The adequate operation occurs when the cement slurry distribution at the wall is homogeneous. In this work, experimental and numerical studies of Newtonian and non-Newtonian fluid displacement through concentric and eccentric annuli are performed. The numerical solution of the governing conservation equations of mass and momentum is obtained with Fluent and OpenFOAM softwares, using the finite volume technique and the volume of fluid (VOF) method. The experiments were performed using a scaled oil well model, where the displacement efficiency was evaluated measuring the density of the mixture at the annuli outlet. Tests are performed using model fluids. The effect of flow rate, density ratio, fluids rheology and geometry configuration on displacement efficiency is investigated. Comparison of experimental and numerical results shows good agreement, validating the numerical procedure.*

Keywords: *fluids displacement, non-newtonian fluids, completion operation*

1. INTRODUCTION

The displacement of drilling mud by cement slurry in completion operations of oil and gas wells involves a time-dependent displacement of non-Newtonian fluids in concentric and eccentric annuli. The success of this operation guarantee the lifetime of the wells. The adequate operation occurs when the cement slurry distribution at the wall is homogeneous.

As means of having a successful operation, it is of highly importance that the displacement process ends with the cement paste homogeneously distributed at the well wall. From the industrial perspective, a good displacement corresponds to the displacement of the in situ fluid perfectly, all around the annulus, with little instability at the interface and with the interface moving steadily at the mean pumping speed. Moreover, the cement paste must have the desired mechanical properties, such as adherence, compression resistance and impermeability since the cemented regions works with dual purposes. First, the cemented casing serves to uphold the wellbore, preventing collapse. Second, the cement provides a hydraulic seal on the outside of the steel tubing. A hydraulic seal is necessary in order to isolate the different fluid-bearing zones of the rock formation from one another and from the surface. Therefore, it is necessary to remove all drilling mud from the annular space between the rock formation and the casing (or the drilling column), by pushing it with the cement paste. To avoid contamination, which would affect the cement properties, one or more spacer fluids are inserted between the drilling mud and the cement paste. Failure in achieving proper zonal isolation can incur a significant economic effect in terms of loss of well productivity, and can also have adverse environmental effects, not to mention time and money consumed in a poorly cemented well. Figure 1 shows examples of well with a bad cementation.

The analysis of the replacement process of a fluid by another, with different physical properties, is characterized by the simulation of a multiphase flow. The solution of the governing equations aims to represent the evolution of the interface shape between each pair of fluids (cement/spacer fluid and spacer fluid/drilling mud) during the displacement process. This is a complex problem, specially when the fluids present non-Newtonian behavior, which is the case of drilling muds and cement slurries. Spacer fluids typically are a mixture of water and polymers, and can also present non-Newtonian behavior. The numerical simulation of flows is a powerful tool in the evaluation of different processes in the industry. Particularly in the oil industry, an experimental investigation in an oil well is an expensive task, and sometimes not operationally feasible (Haut and Crook (1979)).

Most previous studies about the subject aimed the representation of cementing operations, where complete fulfillment of the annular space with the cement slurry is the optimal condition for the zonal isolation. Some works (Haut and Crook (1979); Haut and Crook (1982); Sauer (1987); Lockyear and Hibbert (1989)) show that the process of fluid displacement through vertical oil wells is mainly governed by the viscosity ratio between fluids, the eccentricity of annular space

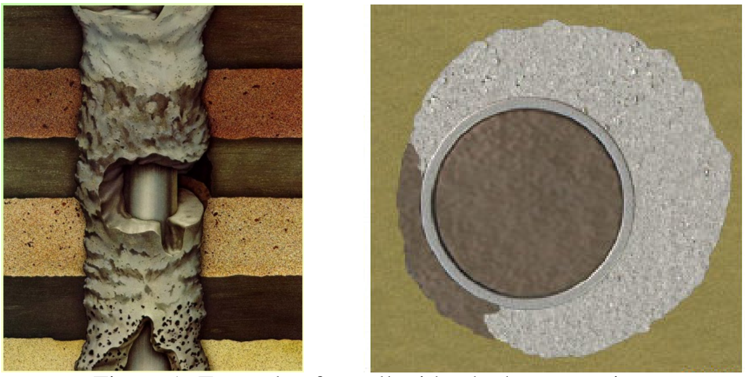


Figure 1: Example of a well with a bad cementation.

between the column and the casing, the flow rate and the density ratio. Theoretical expressions for the breakthrough time were obtained as a function of viscosity ratios, pressure gradient, tube size and rheological properties of the displacing fluid. Good agreement between theoretical and experimental results were obtained for certain ranges of these parameters. Jakobsen *et al.* (1991) analyzed experimentally the effects of viscosity ratio, buoyancy force and turbulence intensity in mud displacement through an eccentric annular tube. The results obtained show that the displacement is more efficient at the largest region, and that turbulence reduces the mud channeling at the narrowest region of the flow. Tehrani *et al.* (1992) performed a theoretical and experimental study of laminar flow of drilling fluids through eccentric annular spaces. They observed that as the eccentricity increases, the displacement becomes worse and describes an experimental rig for fluid displacement in an annulus with variable eccentricity and inclination and it was shown that increasing the volume of displacing fluid the efficiency increases. They also observed that eccentricity has a great effect on the displacement, and showed that minimum efficiency occurs at about 50% of eccentricity. For vertical displacements, it is also shown that the process is more efficient for higher densities differences between the displacer (higher density) and displaced fluids. Vefring *et al.* (1997) analyzed, numerically and experimentally, the influence of rheological and flow parameters in the displacement of a drilling mud followed by cement slurry. The results obtained indicate that numerical simulations provide good results in this kind of problems. Frigaard *et al.* (2002) and Frigaard and Pelipenko (2003) present some theoretical results of cement displacement through eccentric annuli, considering a two dimensional situation. They show that the displacement front may reach a steady regime for some combinations of physical properties. For these cases, an analytical expression for the interface shape is obtained. Guillot *et al.* (1990) performed a theoretical approximate analysis of the flow of a washer fluid pushing a drilling mud through eccentric annuli. All the results were obtained with the washing fluid density greater than the mud density, and they concluded that turbulent flows present smoother interface shapes than the laminar ones. Dutra *et al.* (2004) analyzed numerically the flow of two adjacent fluids through annular eccentric tubes. The effects of rheological parameters and eccentricity were investigated, for different flow rates. The results obtained show that the displacement is better when a more viscous fluid is used to push the other fluid. Also, it was observed that the interface shape is a function of flow regime and viscosities ratio. However, it is insensitive to eccentricity. The effects of density and rheology differences between Newtonian fluids displacing non-Newtonian fluids and vice-versa, were analyzed by Dutra *et al.* (2005).

In this work, experimental and numerical studies of Newtonian and non-Newtonian fluid displacement through concentric annuli were performed. The numerical solution of the governing conservation equations of mass and momentum was obtained using the open source software OpenFOAM. The software uses the finite volume technique and the volume of fluid (VOF) method. The experiments were performed using a scaled oil well model, where the displacement efficiency is evaluated measuring the density of the mixture at the annuli outlet. Tests are performed using model fluids. The effect of flow rate, density ratio, fluids rheology and geometry configuration on displacement efficiency is investigated. Comparison of experimental and numerical results shows good agreement, validating the numerical procedure.

2. EXPERIMENTAL ANALYSIS

The experiments were performed using a scaled oil well model. The test section consist in a transparent vertical flow section of an outer tube (OD=34 mm) and an inner tube (ID=16 mm), with a length of 1070 mm. The fig. 2 present the test section and a displacement example.

In the experimental procedure, the annular space is filled with the displacing fluid. Next, a positive displacement pump circulates water through the annulus at constant rates. A density meter is located in the outlet and the mixture fluid density is measured. Different configurations of geometry is possible (concentric, eccentric, vertical and inclined). The displacement efficiency is evaluated comparing the mixture fluids density at the outlet vs. the pumped volume of the fluids.

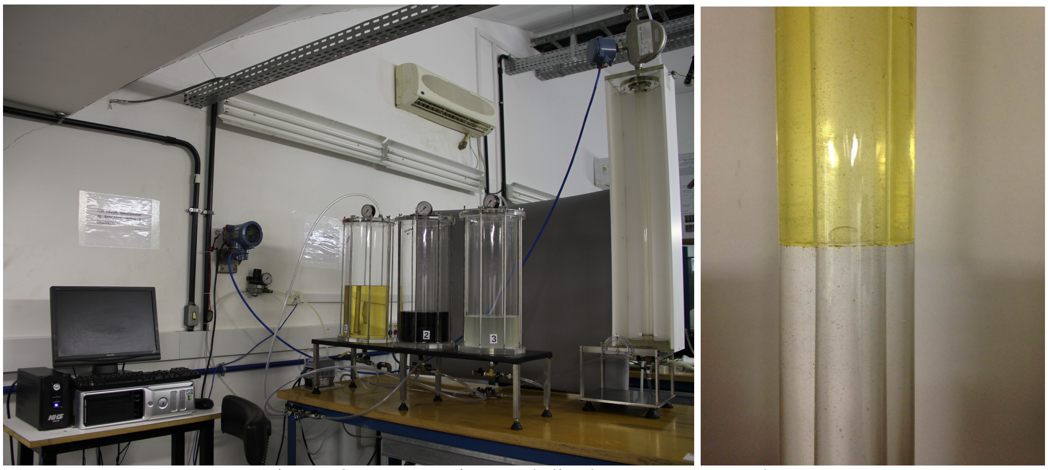


Figure 2: Test section and displacement example.

3. MODELING

The numerical solution of concentric annuli flow of non-Newtonian fluids was analyzed using a three dimensional model. The fluids flow vertically through an annular space. The solution assumptions were that both fluids phase were incompressible, flow was laminar and transient. The boundary conditions were no-slip at walls, uniform velocity at inlet and fully developed flow at the outlet. The computational domain is created with the same dimensions of the experiment. The governing equations presented above are discretized via the finite volume method described by Patankar (1980), using the PISO algorithm (Patankar (1980)) to couple velocity and pressure. The numerical results are obtained using the open source software OpenFOAM.

The volume of fluid method (VOF) was used to take into account the multiphase flow. The VOF method solves a set of mass conservation equations and obtains the volume fraction of each phase α_j through the domain, which should sum up unity inside each control volume. Therefore, if $\alpha_i = 0$, the cell is empty of the phase i; if $\alpha_i = 1$, the cell is full of the phase i and if $0 < \alpha_i < 1$, the volume contains the interface between the phases. The properties appearing in the transport equations ϕ are determined using an average of the property value among the n phases. In the problem studied, three phases are considered. Therefore,

$$\phi = \alpha_2 \phi_2 + (1 - \alpha_2)\phi_1 \tag{1}$$

The interface between phases is obtained by the solution of continuity equation for α_i for the $n - 1$ phases:

$$\frac{\partial \alpha_i}{\partial t} + u_j \frac{\partial \alpha_i}{\partial x_j} = 0 \tag{2}$$

where x_j are the coordinates and u_j are the velocity components. The volume fraction of one of the phases is obtained with the following constraint equation:

$$(\alpha_1 + \alpha_2) = 1 \tag{3}$$

The momentum conservation equation is presented below, for incompressible fluids.

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_k)}{\partial x_i} = -\frac{\partial P}{\partial x_k} + \frac{\partial}{\partial x_i}\left[\eta\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right)\right] + \rho g_k \tag{4}$$

where ρ is the density, P is the pressure and g is the gravity. The non-Newtonian behavior of the fluids is modeled by the Power-Law constitutive equation (eq. 5), based on real data obtained experimentally.

$$\eta = k\,\dot{\gamma}^{n-1} \tag{5}$$

3.1 Dimensionless quantities

Some dimensionless quantities were defined to analyze the results. The ρ^* is the dimensionless density, evaluated using the outlet, displaced and displacer fluids densities (ρ_{outlet}, ρ_1 and ρ_2) respectively. The V^* is the ratio between the pumped volume (V_b) and the volume of one annuli (V_a). The ρ_r , μ_r (Newtonian fluids) , η_r (non-Newtonian fluids) quantities are density and viscosity ratios between displaced (1) and displacer (2) fluids.

$$\rho^* = \frac{\rho_{outlet} - \rho_1}{\rho_2 - \rho_1} \quad and \quad V^* = \frac{V_{pumped}}{V_{annuli}} \tag{6}$$

$$\rho_r = \frac{\rho_2}{\rho_1}, \quad \mu_r = \frac{\mu_2}{\mu_1} \quad and \quad \eta_r = \frac{\eta_2}{\eta_1} \tag{7}$$

3.2 Fluid Rheology

In preliminary non-Newtonian results, the experimental data were obtained using xanthan gum as displaced fluid. Solutions of glycerin (30% and 60%) were the displacer fluid. The Flow curve for xanthan gum 0.1% was shown in Fig. 3. The viscosity model used was Power-Law (eq.5).

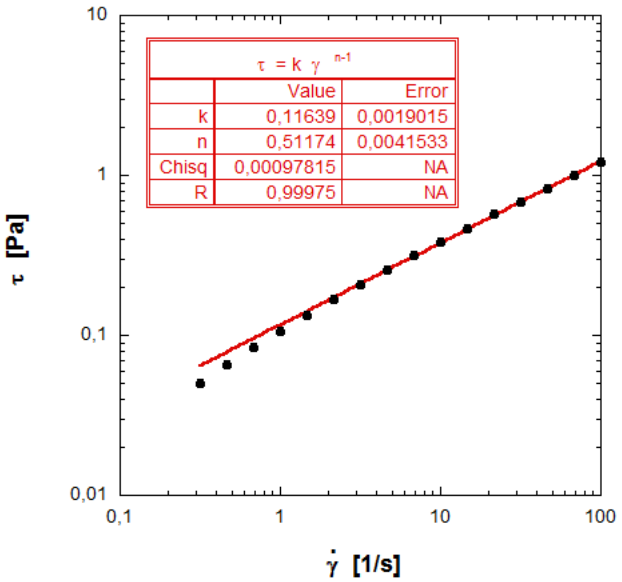


Figure 3: Fluid rheology.

The table 1 shows the glycerin solutions properties. Glycerin solution of 60% was denser and more viscous than the 30% solution.

Fluids	ρ [kg/m^3]	μ [Pa.s]	ν [m^2/s]
glycerin 30%	1071.9	0.00225	2.09908e-6
glycerin 60%	1163.6	0.01195	1.0267e-5

Table 1: Properties of glycerin solutions.

4. RESULTS

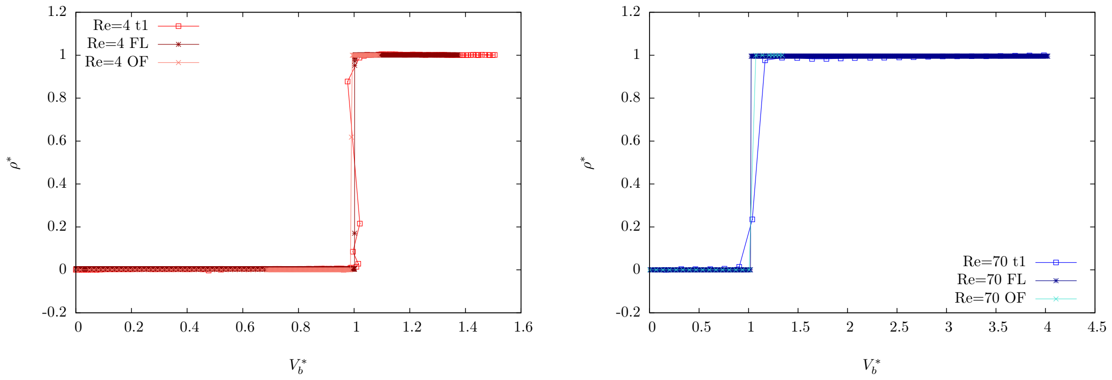
All experimental data were obtained in vertical positions and concentric configurations. First of all, a Newtonian pair of fluids were used to validate the test section and compare numerical results.

The Newtonian pair of fluids were water (displaced fluid) and ethylene glycol (displacer fluid). The density and viscosity ratio were $\rho_r = 1.11$ and $\eta^* = 19.94$, respectively. The result of this displacement was a plug type interface. The numerical results were obtained using the commercial software ANSYS Fluent and the open source software OpenFOAM. All numerical results were in good agreement with experimental data. Figure 4 shows ethylene glycol displacing water for Re=4 and Re=70.

After Newtonian validation, tests using a non-Newtonian fluid was performed. The new pair of fluids chosen were xantham gum 0.1% as displaced fluids and solutions of glycerin as displacer fluids. Table 2 shows the tests studied.

Cases	Displaced	Displacer	ρ_r	η_r	Re
1	GX 0.10%	Glycerin 30%	1.070	0.0654	241
2	GX 0.10%	Glycerin 30%	1.070	0.1000	570
3	GX 0.10%	Glycerin 60%	1.164	0.3500	49
4	GX 0.10%	Glycerin 60%	1.164	0.5300	116

Table 2: Cases studied.

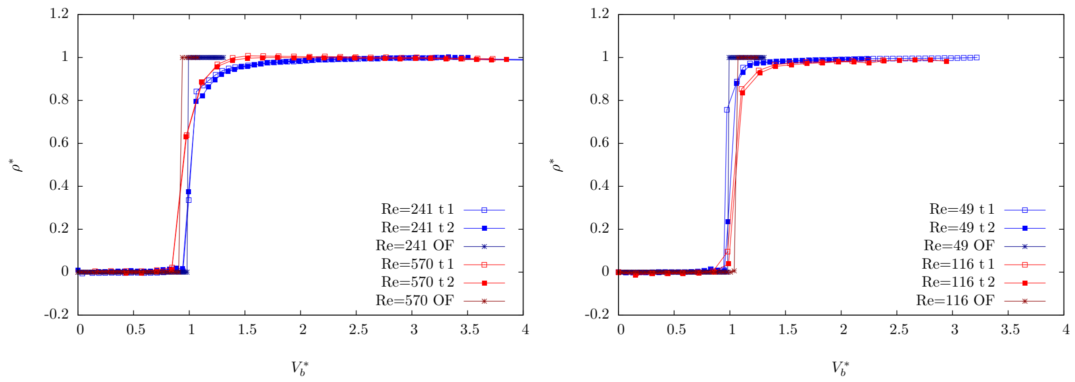


(a) Re=4. (b) Re=70.

Figure 4: Newtonian validation: ethylene glycol displacing water (ρ_r =1.11 and η^* =19.94).

Cases 1 and 2 show glycerin 30% displacing xanthan gum 0.1% for Re=241 and Re=570 and cases 3 and 4 show glycerin 60% displacing xanthan gum 0.1% for Re=49 and Re=116. Figure 5 present the results of all cases.

Analyzing the effect of flow rate, using the glycerin 30% as displacer fluid, there was a slightly difference between Re numbers and displacement efficiency (fig. 5a). The same behaviour was observed using the glycerin 60% as displacer fluid. Increasing the flow rate, the displacement efficiency increases (fig 5b).



(a) Glycerin 30% displacing xanthan gum 0.1%. (b) Glycerin 60% displacing xanthan gum 0.1%.

Figure 5: Solutions of glycerin displacing xanthan gum 0.1% for concentric geometry configuration.

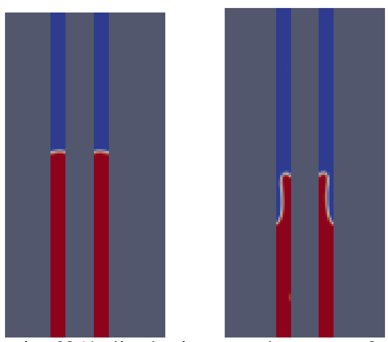


Figure 6: Phase field of glycerin 60% displacing xanthan gum 0.1% for Re=49 and Re=116.

Figure 6 shows the phase field of glycerin 60% displacing xanthan gum 0.1% for Re=49 and Re=116. Numerical and experimental results were in good agreement.

5. FINAL REMARKS

The experimental and numerical results are in good agreement. Further tests using different concentrations of xanthan gum and eccentric geometry configuration will be performed.

Ongoing tests using viscoplastic and thixotropic fluids.

6. ACKNOWLEDGEMENTS

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