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NON-NEWTONIAN FLUID DISPLACEMENT IN ECCENTRIC ANNULI: EXPERIMENTAL AND NUMERICAL STUDY

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Abstract. *In drilling and cementing processes of oil wells, the mud used to drag the gravel, to lubricate and to cool the drill is removed and substituted by a cement mixture. This substitution is obtained by the displacement of a fluid by another in the annuli space between the rocky formation and the casing. For best results, intermediate fluids, also called spacers, are used between the drill mud and the cement mixture. The displacement process is very complex due to geometry and fluids characteristics. The annular space is eccentric in most cases, and both drilling mud and cement mixtures are non-Newtonian fluids. In this work, an experimental and numerical study is performed to analyze this process. A vertical experimental plant was constructed to simulate the fluid displacement through eccentric annuli. The interface shapes between two adjacent fluids had been visualized using a digital CCD camera . The images were compared with the results obtained in the numerical simulations. The numerical solution is obtained via the Finite Volume technique and using the Volume of Fluid method. The effects of eccentricity, displacement velocity and rheological parameters on the displacement efficiency were investigated, Based on these results we can estimate the minimum length for the spacers, between the drilling mud and the cement mixture, that optimizes the displacement process.*

Keywords: Rheology, Cementing process, Multiphase Flow, Eccentric Annuli.

1. Introduction

During drilling operation of oil wells, drilling muds should lubricate and cool the drill, and remove the produced drilling cuts. After this process, it should be removed and replaced by a cement paste, which should provide the well integrity after the cement solidification (cure time). An oil well lifetime is strongly influenced by the cementing operation. In this process, the cement pushes the drilling mud in a laminar or turbulent flow, through an eccentric annular space between the rock formation and the casing. A perfect operation is when all of drilling mud is removed. It is worth noting that it is very important to avoid the contamination of the cement by the drilling mud, in order to prevent from the lost of the desirable cement properties. Therefore, some intermediate fluids, called washing or spacer fluids, are inserted between them. These fluids typically are a mixture of water and detergents, and behave as Newtonian fluids, while drilling muds and cement pastes are typically highly non-Newtonian in nature.

The interface shape between these fluids plays a crucial role during the flow. For a better displacement, the interface shape should be as flat as possible. Sharp interfaces are associated to a channeling phenomenon, where the displacer fluid crosses the displaced one, making the process very inefficient. This undesirable phenomenon may be due to the viscosities ratio or densities differences between the fluids, non-symmetric velocity profile (in the eccentric situations) or flow regime.

Some works (Haut e Crook, 1979; Haut e Crook, 1981; Sauer, 1987; Lockyear e 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 between the column and the casing, the flow rate and the densities ratio. Jakobsen et al. (1991) analyzed experimentally the effects of viscosities ratio, buoyancy force and turbulence intensity in mud displacement through an eccentric annular tube. The results obtained show that 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. For vertical displacements, it is also showed that the process is more efficient for higher densities differences between the displacer (higher density) and displaced fluids. Vefring et al. (1997) analyzed numerical and experimentally, the influence of rheological and flow parameters in the displacement of a drilling mud followed by a cement paste. The results obtained indicate that numerical simulations provide good results in this kind of problems. Frigaard et al. (2002 e 2003) present some theoretical results of cement displacement through eccentric annuli, considering a two dimensional situation. They show that the displacement front may reach permanent 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 washing 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.

The main goal of present work is to analyze experimentally and numerically the displacement of a polymeric liquid pushing a Newtonian oil. To validate the numerical results, they are compared to the experimental ones. Therefore the influence of geometric and rheological parameters on the process can be investigated numerically, in order to improve the displacement process efficiency.

2. Experimental Methodology

The experimental methodology is divided in two parts: the apparatus and the rheology characterization.

Once determined that density, viscosity, eccentricity and pump rate are main parameters, they must be presented dimensionless, using the Reynolds number, which is given by:

$$\mathrm{Re} = \frac{\rho v D_h}{\eta_c} \tag{1}$$

where v is the mean entrance velocity, ρ is the density, D_h is the hydraulic diameter (= difference between outer and inner tube diameters) and η_c is the characteristic viscosity, evaluated at a characteristic deformation rate, given by:

$$\dot{\gamma}_c = \frac{2v}{D_h} \tag{2}$$

The eccentricity using the STO concept is defined in equation (3), where C is the minimum gap between inner and outer cylinders, A is the outer cylinder radius, and B is the inner cylinder radius.

$$STO = \frac{C}{A - B} \tag{3}$$

The experimental section, whose details are shown in figure 1 and 2, is formed by two cylinders one inside the other. The outer cylinder, which is made of transparent Plexiglas, has an inner diameter of 92mm, and the inner one is made of stainless steel and has an outer diameter of 42mm. Therefore, the hydraulic diameter is $D_h = D_o - D_i = 50$mm. The test section was constructed with 2m length annular geometry, and a preceded plenum chamber for flow development, separated by a valve. The inner cylinder is connected with the outer one by screws and steel bars, which can slide and promote the annular eccentricity from STO=1 (concentric) to STO=0 (fully eccentric).

To perform the test, with the valve closed, the annular section is filled with the liquid to be displaced from the top of the apparatus. At time zero, the valve is opened and the displacing liquid is pumped, at a controlled flow rate, and starting to displace the first one. The displacement process occurs from the bottom to the top and it ends when the displacing liquids starts to get out.

The pump connected in the system is a stainless single screw pump with a progressive cavity in order to avoid the polymeric chain to be damaged. The equipment is controlled with a frequency inverter to vary the pump rate until a maximum 15000 L/h or 4,2 Kg/s for water based liquids. The pump and frequency inverter were calibrated together with a chronometer and load cell.

The interface shape is captured with a CCD camera. It is positioned at the end of the test section, 1,6m from the start point. The interface shape is a function of the materials properties, eccentricity and flow parameters. A visualization section filled with glycerin was developed in order to avoid lens effect due to acrylic curvature.

The tests were performed with transparent liquids with rheological properties similar to the cement paste and the spacer fluid. Therefore, it was used an aqueous polymeric solution displacing a mineral Newtonian oil.

The eccentricity and pump rate were the parameters to be varied. The values of STO (i.e. eccentricity) were 1 (concentric cylinders), 0.5 and 0 (maximum eccentricity). The pump rates were estimated using the dimensionless

Reynolds number. The preliminary results were obtained with two levels of velocity: 0.1524 and 0.3048 m/s, which are equivalent to 1 and 2 BPM (barrels per minute), practiced in real oil well cementing operation.

The images obtained were exported to a computer and compared with those obtained in the numerical simulation, to validate its results.

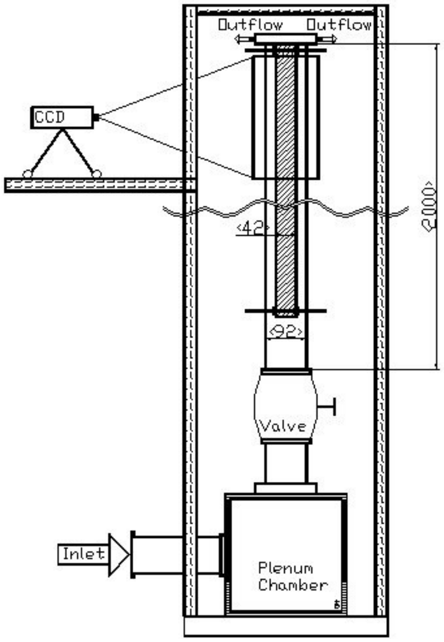


Figure 1 – Experimental Apparatus

Figure 2 – Experimental Apparatus

2.1 Rheological Test

Several tests were performed for the rheological characterization of real cement paste. The rheological properties were obtained using the rotational rheometer "Advanced Rheometric Expansion System" (ARES, Rheometric Scientific), with cone-and-plate geometry, 50 mm diameter and a gap equal to 0.05 mm. The viscosity and shear stress were measured for a given shear kinematics. The tests were performed at 25ºC. The results obtained are shown in Figs. 3 and 4.

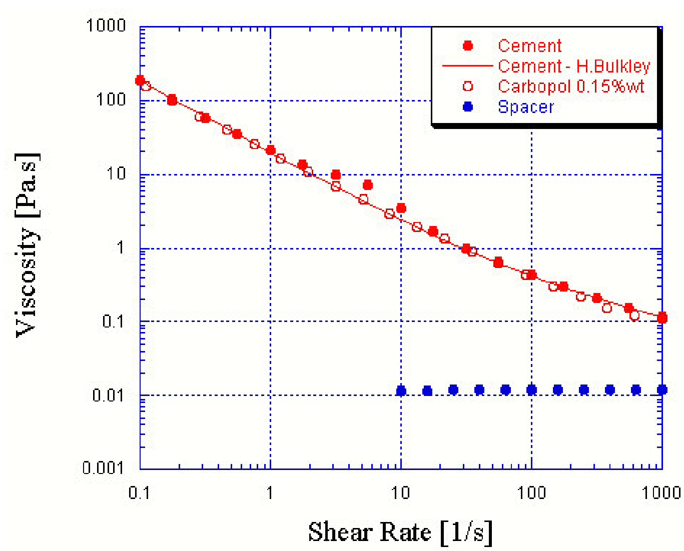


Figure 3. Viscosity x Shear Rate
Cement and Carbopol 0.15%wt fitted with Herschel-Bulkley Model. Newtonian Spacer.

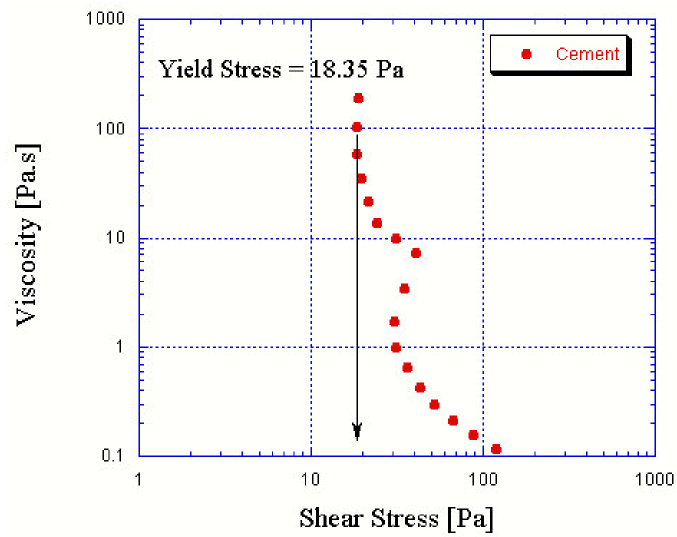


Figure 4. Viscosity x Shear Stress – Cement Yield Stress

Figure 3 shows a Non-Newtonian and shear-thinning behavior for the cement paste, and a Newtonian (constant viscosity) for the spacer. Fig. 4 shows a viscoplastic property for the cement, represented by the yield stress. Fig. 3 shows also the comparison of the viscosity functions for the polymeric solutions and cement. Cements can be well represented by the polymeric solutions. These liquids were developed in the laboratory and were used in the experimental apparatus. The spacer liquid is represented by a mineral oil with the same viscosity, 0.012 Pa.s

2.2 Liquids Mechanical Behavior

The non-Newtonian behavior of the polymeric solutions was modeled by the Generalized Newtonian Fluid constitutive equation, where the extra-stress tensor is given by (Bird *et al*, 1987):

$$\underline{\underline{\tau}} = \eta(\dot{\gamma})\underline{\underline{\dot{\gamma}}} \tag{4}$$

where $\dot{\gamma} = \sqrt{1/2 \mathrm{tr} \underline{\underline{\dot{\gamma}}}^2}$ is the deformation rate modulus, $\underline{\underline{\dot{\gamma}}} = \left(\nabla \underline{u} + \nabla \underline{u}^T\right)$ is the rate-of-deformation tensor and η is the viscosity function, which is chosen to fit the liquid rheological behavior with experimental data.

The *Herschel-Bulkley* model, described by the equation bellow, was used to model the cement mixture.

$$\begin{cases} \eta = \dfrac{\tau_0}{\dot{\gamma}} + K\dot{\gamma}^{n-1} & \text{se} \quad \tau \geq \tau_0 \\ \dot{\gamma} = 0 & \text{se} \quad \tau < \tau_0 \end{cases} \tag{5}$$

Accordingly to figure 4, when the stress modulus is lower than 18.35 Pa, the fluid has a very large viscosity, and behaves as a solid material (Barnes, 2000). This critical stress is called yield stress (τ_0).

The following rheological parameters were obtained from the curve fitting:

- Cement paste and Carbopol 0.15%wt (Herschel-Bulkley model): τ_0 = 18.35 Pa, K = 1.5 Pa.s^n, n = 0.6.
- Spacer fluids and mineral oil (Newtonian): μ = 0.01 Pa.s

The densities used were held constants and equal to: $\rho_{carbopol}$ = 993.4 Kg/m^3, ρ_{oil} = 849.7 Kg/m^3.

3. Numerical Methodology

The numerical solution of the flow was obtained via the finite volume technique and the volume of fluid method (VOF), using the Fluent Software (Fluent Inc., 2003). 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

- α_i=0, the volume does not contain the phase *j*;
- α_i=1, the volume contains only the phase *j*;
- 0< α_i <1, the volume contains the interface.

In this study, only two phases are present. The properties appearing in the transport equations φ, are given by:

$$\varphi = a_2\varphi_2 + (1 - a_2)\varphi_1 \tag{6}$$

The interface between phases is obtained by the solution of continuity equation for α_j:

$$\frac{\partial \alpha_i}{\partial t} + u_i \frac{\partial \alpha_i}{\partial x_i} = 0 \tag{7}$$

The volume fraction of the other phase is obtained with the following constraint equation (Fluent User's Guide):

$$(\alpha_1 + \alpha_2) = 1 \tag{8}$$

The momentum equation is given by:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_k)}{\partial x_i} = -\frac{\partial P}{\partial x_k} + \frac{\partial}{\partial u_i}\left[\eta\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_i}{\partial x_i}\right)\right] + \rho g_k \tag{9}$$

In the above equation, x_i are the coordinates, u_i are the velocity components, P is the pressure, ρ is the density and η is the viscosity function.

The numerical solution was obtained for half of the annular space, due to flow symmetry. Figures 5 and 6 show the numerical mesh, with 200 axial, 20 azimuthal and 20 radial control volumes, which lead to 80000 cells. The boundary conditions were: velocity prescribed at the inlet; fully-developed condition at the outlet; impermeability and no slip wall condition at cylinder walls; zero-shear slip at the symmetry plane.

The numerical simulation used a standard pressure and power-law scheme for momentum discretization, and the PISO algorithm for the pressure-velocity coupling. The under-relaxation factors were 0.3 for pressure; 0.7 for momentum and 0.2 for volume fraction. The problem is transient and used a first-order implicit formulation with a time step of 0.0001 seconds.

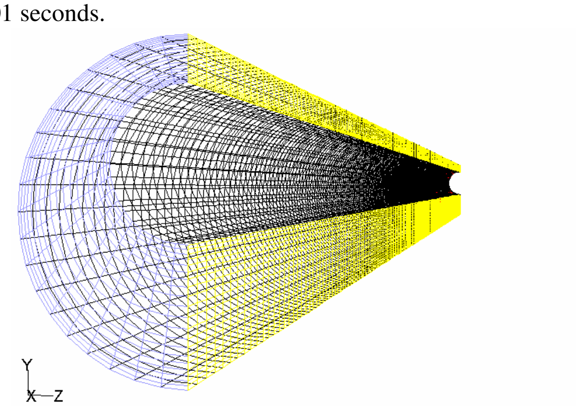


Figure 5 – 3D Mesh – Perspective View – STO 0.5

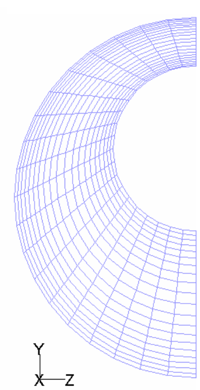
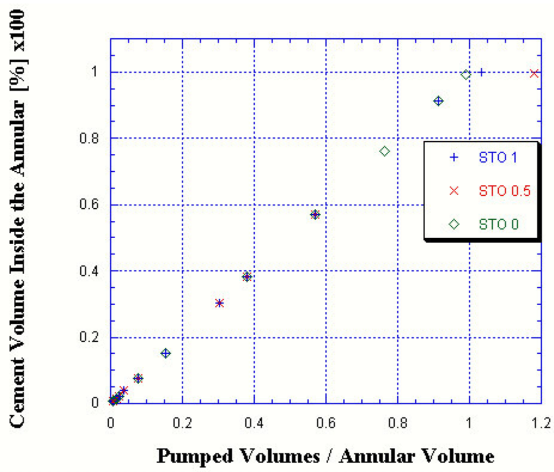
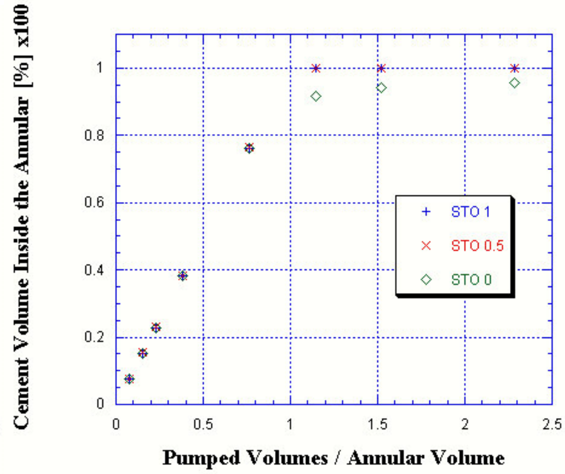


Figure 6 – Transversal View – STO0.5

The input parameters are the velocity inlet, the viscosity models and its parameters, density and superficial tension in the liquid-liquid interface which is 0.02 N/m. The contact angle (wettability) of the interface and the wall is also an input parameter. Several tests were performed to evaluate the influence of the contact angle on the interface shape. It was observed that its effect is located in a very small region close to the wall, so that the interface shape remains the same.

The results obtained are, in a first moment, the phases contour. They are compared with the experimental interfaces images, in order to validate the numerical solution. Therefore, the numerical procedure can be used to investigate the effect of a large number of parameters in the process, which would be too expensive to be done experimentally. The process efficiency is evaluated plotting the residual displaced liquid in the computational domain (annulus) during the pump time. Figures 7 and 8 show how the process efficiency can be estimated. In this case, cement pushes spacer in a high pump rate of 1 and 10 BPM for three different eccentricity values. A perfect displacement shows that after one displacing volume pumped equal the domain volume, the remaining displaced liquid will be equal to zero. In other words, the graphic shows a linear curve with a slope equal to one.





Figures 7 and 8 – Process efficiency. Cement displacing spacer in 1 and 10 BPM for three eccentricities.

4. Prelimary Results

By this moment five tests were performed, all with Carbopol 0.15%wt displacing the Newtonian Oil. Three eccentric configurations and 2 different pump rates were analyzed.

The experimental visualizations of the interface shape are compared to the results obtained with numerical simulation using Fluent software. The results are shown in figures 9, 10, 11, 12 and 13. Figures 9 and 10 show the numerical and experimental results for the highest eccentricity (STO=0), and flow rate equal to 1 BPM and 2 BPM, respectively. Figure 11 shows the results for an intermediate eccentricity, STO=0.5, and flow rate equal to 1BPM. Figures 12 and 13 show the results for the concentric case (STO=1), and flow rate equal to 1BPM and 2 BPM, respectively.

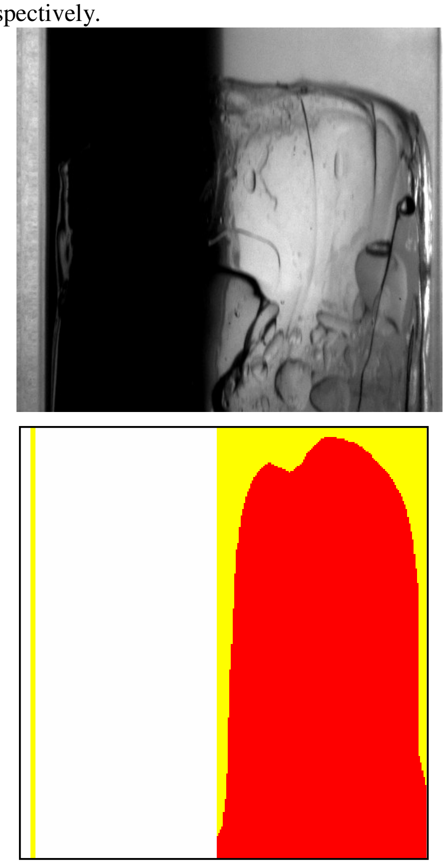


Figure 9. Carbopol 0.15%wt displacing Oil
STO 0 – 1BPM
Experimental (above) – Numerical (below)

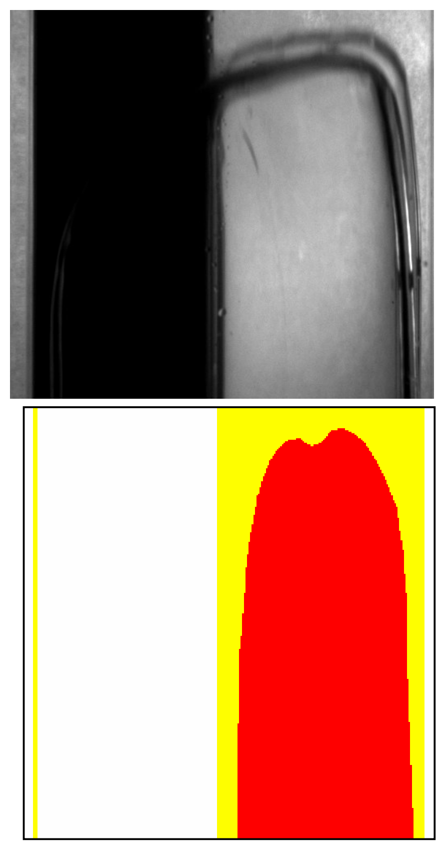


Figure 10. Carbopol 0.15%wt displacing Oil
STO 0 – 2BPM
Experimental (above) – Numerical (below)

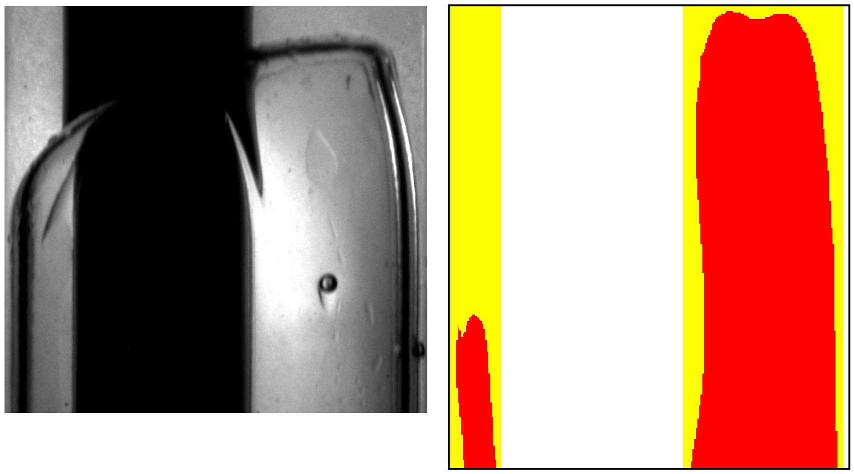


Figure 11. Carbopol 0.15%wt displacing Oil
STO 0.5 – 1BPM
Experimental (left) – Numerical (right)

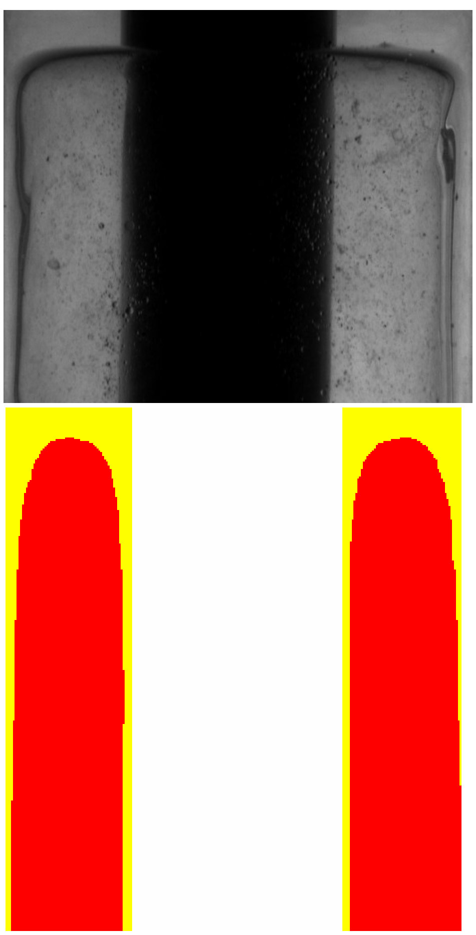


Figure 12. Carbopol 0.15%wt displacing Oil
STO 1– 1BPM
Experimental (above) – Numerical (below)

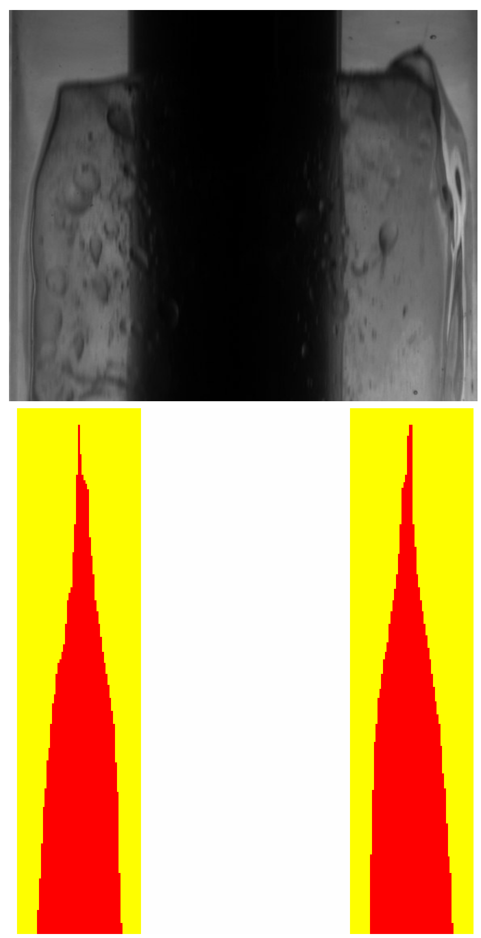


Figure 13. Carbopol 0.15%wt displacing Oil
STO 1 – 2BPM
Experimental (above) – Numerical (below)

The comparisons of numerical and experimental results show a good qualitative agreement. It can be observed that the interface shape is a strong function of the pump rate and of the eccentricity. It is worth mentioning that the ideal situation in a cementation process is the total displacement of the first liquid. The displaced liquid remaining at the wall can be an indication of the process efficiency. The results obtained show that for higher flow rates, i.e., faster displacements, a sharp interface shape occurs and large quantities of oil remain at walls, meaning that the process is not good. However, lower flow rates promote flatter interface shapes and lower quantities of oil at walls, leading to a better displacement efficiency. It can also be observed in the eccentric cases, that flow displacement is faster at larger flow regions.

The images from the numerical simulation are taken from a plane in the symmetry surface. The acquired images with the CCD camera are frontal. If the experimental visualizations were taken from the same plane as the numerical, a better comparison would be realized.

5. Concluding Remarks

In this work an experimental and numerical study of flow displacement of two adjacent fluids through annular eccentric space were performed. The analysis simulates the displacement process that occurs in cementing operation in oil wells, where a cement mixture pushes a spacer fluid, which pushes the drill mud outside the well. Both drill mud and cement are non-Newtonian, and the spacer fluid is usually a Newtonian fluid. The experimental apparatus is constructed to visualize the interface shape between two fluids. The numerical solution is obtained solving the conservation equations via the finite volume technique and using the volume of fluid method. Preliminary results were obtained showing that the experimental and numerical results are in good qualitative agreement. Therefore, the numerical simulation seems to be an important tool to be used to obtain the influence of relevant parameters on process efficiency. It can also be observed that higher flow rates contribute to a sharp interface shape which suggests a poor displacement process. The next tests will be realized in higher flow rate levels, and changing the fluid displacement order, in order to simulate the displacement of the drill mud by spacer fluid. Therefore, a new polymeric liquid concentration will be used, with rheological parameters similar to the ones of a drilling mud. After validation of the software capabilities, it will be used to evaluate the process efficiency. Plotting the remaining displaced liquid in the annulus versus pump time, the cases can be compared quantitatively and a more precise conclusion can be taken.

6. Acknowledgement

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