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EFFECT OF RHEOLOGY ON FLOW DISPLACEMENT DURING CEMENTING PROCESS IN OIL WELLS

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Abstract. *This paper describes a set of numerical simulations of the displacement flow of three non-Newtonian fluids through annular eccentric wells. The main application of this work is the studying of drilling and completion processes of oil wells where a cement slurry pushes the drilling mud, used in the drilling process to lubricate the drill and to remove the produced drilling cuts. To avoid contamination, a spacer fluid is usually inserted between them. Both drilling mud and cement slurry behave as non-Newtonian fluids, and the spacer fluid can be Newtonian or non-Newtonian. The analysis of flow and interface configuration between these fluids helps to determine contamination, and is an important tool for the process optimization. The numerical solution of the governing conservation equations of mass and momentum is obtained with the Fluent software, using the finite volume technique and the volume of fluid method. The effects of rheological parameters, density ratios and pumped volume of the spacer fluid are investigated. The results obtained show that the displacement is better when a more viscous spacer fluid is used. The results also show that using lower amounts of the spacer fluid can lead to contamination, which is worse in the smaller gap region of the annular space, in the case of non-rectilinear well. It was also observed that the density ratios play a major role in the cementing operation.*

Keywords:*annular flows, non-Newtonian, oil wells, multiphase flows*

1. INTRODUCTION

The replacement of drilling fluids with cement to support and to protect casing, as well as to seal formation pressures hydraulically, has been the desire of engineers for over 75 years and is at a point that the mechanics of mud displacement is well understood. Yet there are still many instances of poor placement design in cementing operations. The cementing process in an oil well is a crucial operation that needs to be very well performed, in order to guarantee the desired well life, since the lifetime of the well is strongly influenced by the cementing operation.

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.

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.

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 between the column and the casing, the flow rate and the density ratio. Bakhtiyarov and Siginer (1996) performed a theoretical and experimental analysis of the displacement of Newtonian fluids by non-Newtonian fluids in horizontal cylindrical tubes. 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. Tehrani et all. (1993) 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, are analyzed in Dutra et al. (2005). The present work details flow displacement and fluid contamination predictions to some of the typical completion operations. The numerical solution is obtained using the finite volume technique and the Fluent software. The effect of rheological properties, density ratios and the spacer pumped volume in fluid displacement were investigated.

2. MATHEMATICAL MODELING

The geometry analyzed is shown in Fig. 1. The fluids flow vertically through an annular space, between the rock formation and the casing. The flow is axi-symmetric and transient. Before the beginning of the process simulation ($t < 0$), both the central tube and the annular space are filled with the drilling fluid. When the simulation starts, the spacer fluid is injected at a constant flow rate in the central tube, during a time interval. Then, the cement slurry is injected.

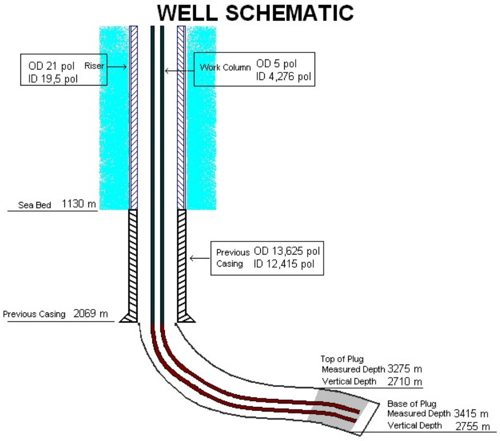

Figure 1. Well geometry

The non-Newtonian behavior of the fluids is modeled by the Power Law fluid constitutive equation, based on real data obtained experimentally. The stress tensor is given by: $\boldsymbol{\tau} = \eta(\dot{\gamma})\mathbf{D}$, where $\mathbf{D}$ is the rate-of-strain tensor, $\mathbf{D} =$

$(\text{grad } \mathbf{v} + (\text{grad } \mathbf{v})^T)$, $\mathbf{v}$ is the velocity vector. η is the viscosity function and $\dot{\gamma} = \sqrt{1/2\text{tr}\mathbf{D}^2}$ is the magnitude of the rate-of-strain tensor. The volume of fluid method (VOF) (Fluent User's Guide, 2010; Hirt et al., 1981) is 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 volume does not contain the phase i;
- $\alpha_i = 1$, the volume contains only the phase i;
- $0 < \alpha_i < 1$, the volume contains the interface;

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,

$$\phi = \alpha_1\phi_1 + \alpha_2\phi_2 + \alpha_3\phi_3 \tag{1}$$

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:

$$\alpha_1 + \alpha_2 + \alpha_3 = 0 \tag{3}$$

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 viscosity function is given by the power-law equation:

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

The two parameters that appear in the viscosity function above, namely K and n, are the consistency index and the behavior index (or power-law exponent), respectively, which are determined by means of least-squares fittings to rheological data.

The boundary conditions are the usual no-slip and impermeability conditions at the solid boundaries, and developed flow at the outlet. At the inlet, the velocity is considered uniform and in axial direction.

3. NUMERICAL SOLUTION

The governing equations presented above have been discretized via the finite volume method described by Patankar (1980), using the SIMPLE algorithm (Patankar, 1980) to couple velocity and pressure. The numerical results were obtained using the Fluent (Fluent Inc.) software. A non-uniform mesh with 6048 control volumes was used in the numerical simulations, after some mesh tests performed.

The simulations performed were defined to represent real operations. However, since the well length is orders of magnitude higher than the well diameter, a scale factor must be applied to the well length in order to obtain reliable results with a reasonable computational time. Otherwise the time required to perform a simulation would take approximately 200 days. The scale factor used was equal to 500, based on tests performed previously.

4. RESULTS AND DISCUSSION

The main goal of this work is to analyze the displacement and contamination at the well, focusing at the bottom region of the well and near the transition from the small annular space to the larger one, where a recirculation zone appears. Three different situations are evaluated, all of them based on petroleum industry real data. According to Fig. 1, well information used are as follow:

- Total length $L = 3425$ m
- Outer diameter of the annular: $D_o = 0.3112$ m
- Inner diameter of the annular: $D_i = 0.1270$ m

- Eccentricity (=distance between the center of the inner and outer tube): $\epsilon = 0.0230$ m
- Standoff: 75% (=1 - dimensionless eccentricity, $STO = 2(1-\epsilon)/(D_o - D_i)$)
- Total lenght scaled: $L_{esc} = 6.85$ m

The mean entrance constant flow rate is equal to 0.0159 m^3/min for all cases. The Reynolds number ($Re = \rho \bar{v} D_h / \eta_c$, where η_c is a characteristic viscosity, evaluated at $\dot{\gamma}_c = 8\bar{v}/D_h$) is always below the critical value of 2300, so the flow is laminar in all regions.

The density and rheological parameters for the fluids are given below.

- Drilling mud: $\rho = 1162.3$ kg/m^3, $K = 2.39$ Pa.s^n and $n = 0.35$
- Spacer fluid: $\rho = 1318.1$ kg/m^3, $K = 2.29$ Pa.s^n and $n = 0.40$
- Cement slurry: $\rho = 1977.1$ kg/m^3, $K = 10.77$ Pa.s^n and $n = 0.30$

The cases analyzed were:

- Case 1: Spacer fluid, pumped volume $V = 9.54$ m^3 (or 60 bbl).
- Case 2: Spacer fluid, pumped volume $V = 12.72$ m^3 (or 80 bbl).
- Case 3: K of the spacer fluid increased in 10%.
- Case 4: Spacer fluid density increased in 19%.
- Case 5: Spacer fluid density increased in 38%.
- Case 6: Spacer fluid density increased in 38%, and drilling mud density decreased 20%, for $V = 12.72$ m^3.
- Case 7: Spacer fluid density increased in 38%, and drilling mud density decreased 20% and cement slurry density decreased 18%, for $V = 12.72$ m^3.

The volume fraction distribution for all seven cases are shown in Figs. 2-7. The orange color is the drilling fluid, the yellow one is the spacer fluid and the gray fluid is the cement paste. The flow goes from the bottom to the top of the well.

Figure 2 shows the volume fractions for cases 1 and 2 at the bottom region of the well. It can be observed that with the increase of the pumped volume of the spacer fluid, the displacement process is more efficient and the chances of contaminating the cement slurry decreases significantly, as expected.

Figure 3 shows the volume fractions for case 3, increasing the consistency index, K, of the spacer fluid, for the pumped volumes of 9.54 m^3 and 12.72 m^3. A more viscous spacer fluid (higher consistency index) leads to an increase in the viscosity ratio between the spacer fluid and the drilling fluid. The results are far better than those observed in fig. 3, since a better rearangement of the fluids at the bottom of the well is noticed, as well as a reduced fingering formation, compared to the cases mentioned above. These results are in agreement with the literature, where it is observed that when a more viscous fluid pushes a lower viscous one the interface shape is flatter, and the displacement efficiency is higher.

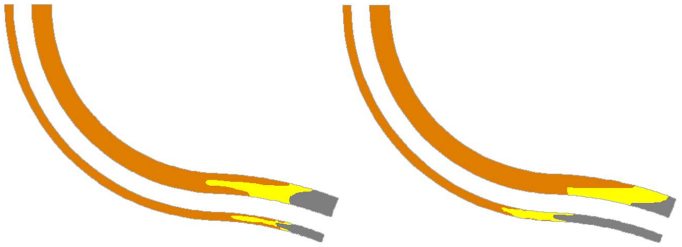

Figure 2. Effect of increasing pumped volume at bottom well region: original case, $V = 9.54$ m^3 case 1 (left) and $V = 12.72$ m^3 case 2 (right) .

Figures 4 and 5 show the volume fractions for cases 4 and 5 with an increase in the density of the spacer fluid, for the pumped volumes of 9.54 m^3 (left) an 12.72 m^3 (right). It can be observed that fingering is reduced in the lower part of the annulus as we raise the density of the spacer fluid, since gravity causes the spacer fluid to flow towards the lower region of the well. However, the hazard of contamination of the cement slurry by the drilling mud in the upper region increases.

Figures 6 and 7 display the volume fraction for cases 6 and 7, decreasing the density of the drilling fluid and of the density of the cement slurry, respectively. In both cases the pumped volume of the spacer fluid is equal to 12.72 m^3. Both cases lead to worse displacement, since the contamination is clearly observed in both simulations. The effect of decreasing

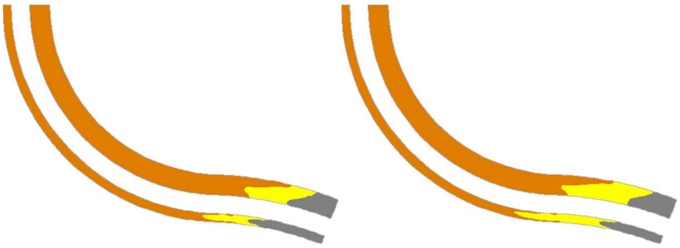

Figure 3. Effect of increasing K for pumped volumes of 9.54 m^3 (left) and 12.72 m^3 (right) of spacer fluid.

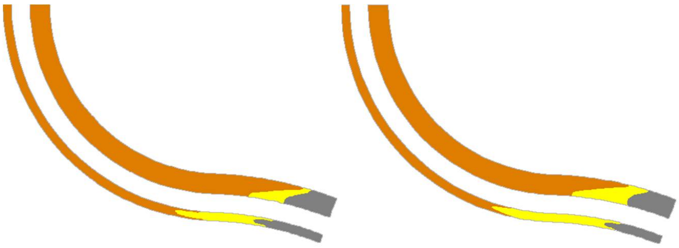

Figure 4. Effect of increasing the density of the spacer fluid to 1569.1 kg/m^3 for pumped volumes of 9.54 m^3 (left) and 12.72 m^3 (right) of spacer fluid

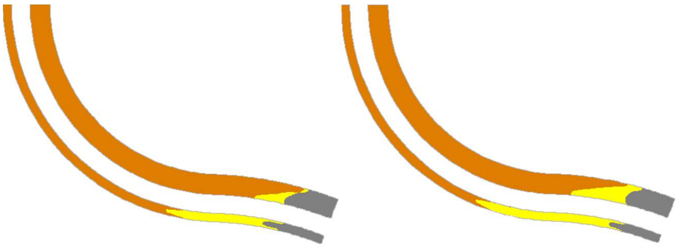

Figure 5. Effect of increasing the density of the spacer fluid to 1821.6 kg/m^3 for pumped volumes of 9.54 m^3 (left) and 12.72 m^3 (right) of spacer fluid

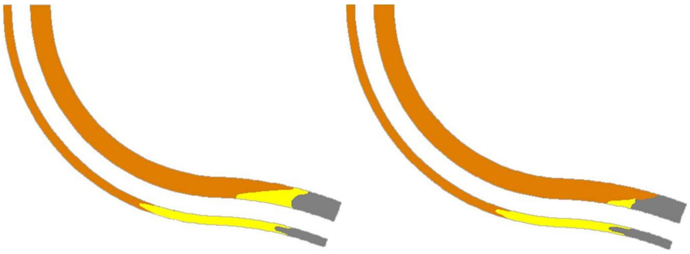

Figure 6. Effect of decreasing the density of the drilling mud from 1162.3 kg/m^3 (left) to 922.5 kg/m^3 (right).

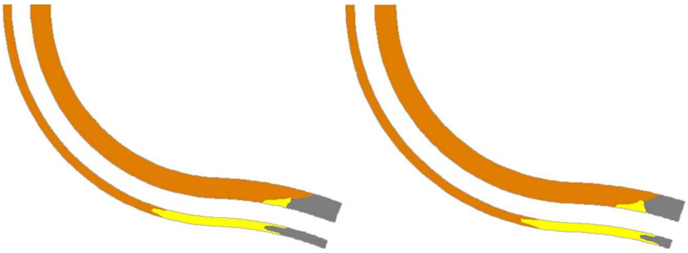

Figure 7. Effect of decreasing the density of the cement slurry from 1977.1 kg/m^3 (left) to 1617.8 kg/m^3 (right).

the density of the drilling fluid is similar to that of increasing the spacer fluid density. Since the drilling fluid is lighter, the spacer fluid moves towards the lower wall, increasing the contamination in the upper region of the annulus. When the density of the cement decreases the contamination in the upper region continues to occur, but the interface shape of the cement front is flatter, which indicates a slightly better performance of the operation (fig.7).

The analysis above shows that contamination regions are identified at the bottom and upper regions of the well in the annular for some situations. Better performance of the displacement process is obtained increasing the viscosity ratio between the spacer fluid and the drilling fluid (by means of increasing the consistency index of the spacer fluid, for instance). Moreover, the volume pumped of the spacer fluid is also an important factor, and higher pumped volumes of the spacer fluid causes decreases the chances of contamination of the cement slurry. The density ratios between fluids also play an important role in the displacement performance.

5. FINAL REMARKS

In this work the displacement of three adjacent fluids through a nearly horizontal oil well was numerically analyzed, using the volume of fluid method and the Fluent software. The Generalized Newtonian Fluid constitutive equation was used, with the Power Law viscosity function to model the non-Newtonian fluids behavior.The flow through the annular region was investigated, in order to evaluate the contamination among the fluids. Several distinct situations were studied, based on real data from the petroleum industry. The effects of increase in the pumped volume and consistency index of the spacer fluid, and density ratios on the displacement efficiency were investigated. From the results obtained, it was observed that a significant improvement on the process efficiency can be obtained increasing the volume pumped and/or the viscosity of the spacer fluid. However, the increase of the spacer fluid density leads to larger chances of contamination in the upper region of the annular space. The decrease of the density of the drilling fluid has the same effect, and the decrease of the cement slurry density slightly improves the process. The results obtained show that the usage of numerical simulations for the prediction of displacement operations can be successfully used to optimize volumes, rheological properties, densities and flow rates throughout the process.

6. ACKNOWLEDGEMENTS

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