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NON-NEWTONIAN FLOW DISPLACEMENT IN WELL OPERATIONS

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Abstract. *Several oil industry operations, such as well plugging and abandonment, cementing operations, and restarting flows of gelled pipes, use the displacement of one fluid by another in annular tubes. There are many variables that can affect the displacement efficiency, namely the rheological behavior of the fluids, the viscosity and density ratios, and the well geometry. The interaction of these parameters can lead to instabilities at the interface between fluids that will result in inefficient flow displacement processes. In these circumstances, an effective procedure is required to prevent issues that could result in dangers and significant financial losses. In this work we present experimental results of the displacement efficiency through an annular tube. The analysis is done for low Reynolds numbers, with a Newtonian (water) fluid being displaced by a non-Newtonian (xanthan gum solution) one, to simulate a plug & abandonment operation. The experimental study is done using a test rig that consist of a steel tubing and a transparent casing with diameters that reflect a real-case scenario. We use two different inclinations and analyze concentric and eccentric situations. To determine the impact of the parameters on the displacement efficiency, a flow visualization is carried out at the experimental rig along with an evaluation of the interface instability.*

Keywords: *Non-Newtonian flow, cementing operations, displacement flows*

1. INTRODUCTION

The displacement flow of complex fluids is found in several industrial processes. In particular, this situation occurs in oil well plugging and abandonment and cementing operations, where a fluid (usually a spacer or a drilling fluid) has to be displaced by a cement slurry through and annular space. If remove mud and spacer are not properly removed from annulus the establishment of zonal isolation with cement can be compromised. Therefore, a perfect displacement must be performed to guarantee a successful operation. However, this is not an easy task to be accomplish because many variables can affect the displacement efficiency. Geometry and flow parameters, fluids rheology and the hierarquy between them, all play a role in the process. Several works have been analyzing the problem throughout the years, both numerically and experimentally (e.g., Lockyear et al., 1990; Jacobsen et al., 1991; Tehrani et al., 1992; Frigaard et al., 2002; Pelipenko and Frigaard, 2004, Dutra et al, 2005; Malekmohammadi et al., 2010; Ytrehus et al., 2017), but there are still several lacks in the literature, mostlty due to the large number of important parameters influencing the flow displacement. The main issues regarding the geometry include eccentricity and well inclination. In respect of flow parameters, inertia and buoyancy forces play an important role, while fluids rheology is also a challenge due to the non-newtoniand fluids behavior, including shear thinning and yield stress of one or both fluids.

Several works 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 (e.g. Haut and Crook, 1979; Haut and Crook, 1982; Sauer, 1987; Lockyear and Hilbert, 1989). Regarding fluids rheology, it was observed that flow displacement of yield stress fluids can lead to unyielded regions, static fluid layers close to the walls and viscous fingering instabilities (Moyers-Gonzalez and Frigaard, 2008; Denn and Bonn, 2010; Lindner et al., 2000). Aranha et al. (2011) numerically investigated how to optimize density and viscosity hierarchy to avoid fluids contamination during displacement, and also analyzed the effect ot string rotation on the displacement efficiency. The effect of eccentricity and density difference was studied in Teharani et al. (1993). The interface between the fluids were investigated in Ytrehus et al. (2017) and Lund et al. (2018) for inclined and irregular geometries. Skadsem et al. (2019a) analyzed experimentally the cementing displacement in critic conditions of irregular wells with highly inclined geometries and large eccentricity.The displacement through irregular geometries was also analyzed in Etrati et al. (2020), Roustaei and Frigaard (2013), Roustaei et al. (2015), Skadsem et al. (2019b), Varges et al. (2020) and Varges et al. (2022). The presence of a washout zone generates unyielded zones that compromise the displacement efficiency.

Despite all the works that have already been published, there is still several challenges to be discussed due to the large number of variables involved in the problem. In this work, we perform experimental tests to analyze the role of well eccentricity and inclination on the displacement of a newtonian fluid by a yield stress one. The cases analyzed intend to simulate the process that happens in a plug & abandonment operation, so only low Reynolds numbers are considered. Moreover, the experiments are performed fixing a pair of fluids that represent a cement slurry displacing brine.

2. EXPERIMENTAL METHODOLOGY

2.1 Fluids

The experimental tests were performed for a fixed pair of fluids to represent the displacement of brine by a cement slurry. To model the cement slurry (displacing fluid) behavior a xanthan gum solution (XG) was used, and the brine (displaced fluid) was replaced by tap water. The tap water used in these tests had a density of 998 kg/m³ and a viscosity of 0.001 Pa.s. On the other hand, xanthan gum was mixed at a volumetric proportion of 2% in water with ≈223 g/l of salt, resulting in a density of 1130 kg/m³. The xanthan gum flow curve was measured with the aid of the rotational rheometer Anton Paar Rheoplus/32 V3, using a plate geometry (CP75) and following a shear rate ramp-down procedure from 1020 s^{-1} to 0.01 s^{-1}. The rheological data was obtained three times for all different samples, and the results show good repeatability. The fluid showed a shear thinning behavior and yield stress, so its rheological behavior was parameterized using the Herschel Bulkley model, where the viscosity function η is given by Eq. (1).

$$\eta = \begin{cases} \frac{\tau_y}{\dot{\gamma}} + K.\dot{\gamma}^{n-1} & \text{if } \tau \geq \tau_y \\ \infty & \text{if } \tau < \tau_y \end{cases} \tag{1}$$

Where τ_y is the yield stress, *K* is the consistency index, and *n* is the power-law index.

Figure 1 shows the xanthan gum flow curve and its respective Herschel Bulkley model parameters defined by minimizing the residual sum of squares of the shear stress. It can be observed that the fluid presents a yield stress equal to 7.33 Pa, K=3.39 Pa.s^n and n=0.413.

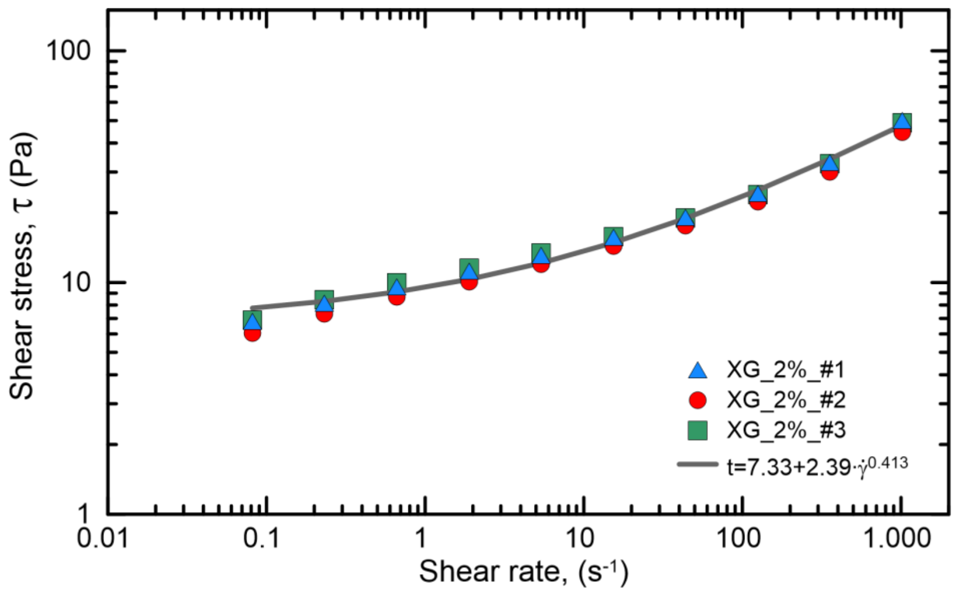

Figure 1. Anton Paar measurements of the XG soluttion (three samples) prior to the displacement tests. The solid line is the corresponding Herschel Bulkley fit to the measurements.

2.2 Experimental setup

The main objective of the experiments is to simulate an actual displacement process from a cementing operation in the field using a laboratory downscale test rig. The test rig consists of a flow loop, where thue fluis are displaced inside an annulus. Table 1 presents the geometry of the lab test rig, and Figure 2 shows the test configuration. The outer tube is transparent, made with Lexan, and the inner tube is made of steel. An eccentricity device mounted on the rig allows adjustment to simulate concentric and eccentric situations. Moreover, an axial vibration tool is included in the rig to allow vibration of the inner duct. The fluids are pumped through the tube using a positive displacement pump, which supplies a constant flow rate controlled by a variable frequency driver.

The experiments were performed considering dynamic similarities with the real case scenario, focusing on the viscosity ratio and Reynolds numbers, which are defined in Eq. (2) and (3).

$$\eta_r = \frac{\eta_c}{\mu} \quad (2)$$

$$Re_c = \frac{\rho_c v D_h}{\eta_c} \qquad Re_a = \frac{\rho_a v D_h}{\mu} \quad (3)$$

Where η_c is the viscosity of the xantham gum evaluated at a characteristic shear rate of $\dot{\gamma}_c = v/D_h$, μ is the viscosity of tap water, v is the fluids velocity, D_h is the hydraulic diameter of the annular section and Re_c and Re_a are the Reynolds numbers of the xantham gum and water, respectively.

Finally, a Coriolis flow meter was attached to the test setup to measure flow rate, density, and temperature at the outlet, while displacing the fluids through the annulus geometry. The tests were performed twice, and showed good repeatability, as it can be observed in Fig. 5. Flow visualization is also performed through the test, using a camera, to verify the interface during the displacement and the amount of fluid left close to the walls.

Table 1. Geometric dimensions for the downscale test rig.

Test rig geometry	**Symbol**	**Value**
Inner pipe diameter (mm)	ID	70
Outer pipe diameter (mm)	OD	50.5
Hydraulic diameter (mm)	Dh = OD - ID	19.5
Total test section length (m)	L	1.516

Figure 2. The laboratory downscale test rig setup.

3. RESULTS

The experimental tests presented focused on the analysis of the effect of well inclination and eccentricity on flow displacement. The cases were analyzed for the same pair of fluids. For all cases, flow rate and density measurements were obtained with the aid of a Coriolis flow meter positioned at the outlet. After fluids preparation, the water is pumped from the storage tank through the tube to fill the annular space. Then, we pump the xantham gum from the tank until it reaches the inlet section. The experiments began just after this, pumping one annular volume of xantham gum throughout the tube. The flow displacement is recorded and the density and flow rate measured in the Coriolis flow meter. In the cases analyzed, the flow rate was fixed at 10 l/min, and it was considered a concentric and one eccentric case (ecc = 0.75). The flow rate used intended to simulate a real case scenario of a plug & abandonment operation, with Re_c=0.78, Re_a=1751, and η_r=2560.

Figure 3 illustrates the annular displacement for the vertical cases, considering concentric tubes and 0.75 eccentricity, and displacing the fluids by an imposed 10 l/min flow rate. Xantham gum (XG) was colored by a blue ink. For the concentric case, the XG displacement is efficient, filling the whole annulus gap, as seen in Figure 3(a). On the other hand, it is possible to observe in Figure 3(b) that there is almost no XG on the narrow side of the annulus for the 0.75 eccentric case. The displacement through the narrow side was not favored because the stresses at the narrow side are lower and do not surpass the xanthan gum yield stress. Therefore, the water remains almost stagnant at this region.

(a) (b)

Figure 3. Xanthan gum concentration after fluid displacement in vertical annular geometries, which (a) represents the concentric case and (b) the 0.75 eccentric case.

Considering the rig inclination, Figure 4 shows the annular displacement behavior for a 60°-inclined well. The eccentricity was again evaluated in comparison to the concentric case, and the 10 l/min flow rate was also maintained. The concentric case resulted in an efficient fluid displacement regardless of the rig inclination. For the eccentric case, although the xanthan gum did not wholly displace the volume of water present in the annulus, this time, gravity acted as a favoring agent for the fluid displacement from the wider region to the narrower one. However, there is a decrease in the displacement efficiency of the yield stress fluid as the displacement front approaches the setup outlet; that is when the fluid column decreases, and consequently, the pressure column also decreases, therefore stresses are lower.

(a) (b)

Figure 4. Xanthan gum concentration after fluid displacement in 60°-inclined annular geometries, which (a) represents the concentric case and (b) the 0.75 eccentric case.

Figure 5 presents the curves of fluid density at the rig outlet, obtained from the Coriolis measurements. These results quantify the flow displacement efficiency during the experiment. At lower times, the density measured is equal to the water density, and it levels up when XG begins to flow out of the annulus. The sooner the density level reaches the XG density the better is the displacement. So, it can be noted that the vertical concentric case presents the best displacement, while in the inclined eccentric it takes more time to obtain a better displacement efficiency.

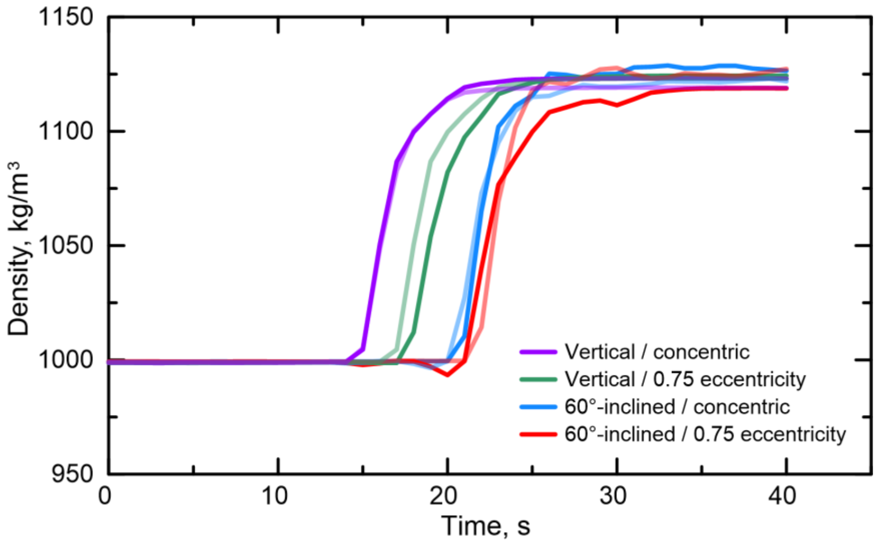

Figure 5. Density variation throughout the fluid displacement from the Coriolis measurements. Each color (light and dark) represent one different geometry.

4. CONCLUSION

The concentric cases analyzed showed good displacement efficiency, regardless of whether the rig was vertical or inclined. Comparatively, it is clear to observe a remaing layer of water in the narrow region of the eccentric cases when displacing the xanthan gum both in the vertical and inclined geometries. For the inclined case with an eccentricity of 0.75, while the displacement may have been favored by the action of gravity, the pressure gradient is lower, and in the end this case presented the worse geometry scenario. Future work will investigate different situations to perform a more complete parametric analysis. These include different eccentricities, flow rates and fluids rheology. Moreover, the tube vibration's effect will be evaluated and numerical simulations will be performed to study a broader range of parameters.

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