Rheological and geometric effects in cementing of irregularly shaped wells

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ABSTRACT

Large numbers of oil and gas wells, in Canada and worldwide, allow leakage to surface from the reservoir. One common reason is associated with unsuccessful mud removal during the primary cementing operations, i.e. the drilling mud remains stuck in the narrow annular region. Several factors have to be taken into account in order to design a successful cement job; namely, the geometry of the well, the rheology of the fluids and the pumping schedule. In this study, we explore how geometric irregularity can combine with fluid rheology to give a wide range of different behaviours.

INTRODUCTION

This paper looks at both geometric and rheological effects on primary cementing displacements, for simplicity focusing on vertical wells. Primary cementing is a process carried out on every oil and gas well (typically at least twice), in which a steel casing is cemented into a newly drilled borehole. The cylindrical casing is lowered into the well creating an annular space between its outside wall and the borehole inner wall. Casings run many hundreds of metres along the well, penetrating different geological strata. A range of casing diameters are used (larger near the top of the well, smaller in production zones), but with an annular gap that is $2-3$cm wide on average. The well is typically full of drilling mud, which is a shear-thinning yield stress fluid, and this must be replaced with a cement slurry to fill the annular space, where it will harden. The objectives are both to zonally isolate different fluid bearing strata in the formation and to provide mechanical support to the well. Primary cementing proceeds by pumping a sequence of fluids down the inside of the casing to bottom hole, returning upwards in the annulus from the bottom. These fluids are designed (density and rheology) to help with the removal of the drilling fluid. An overview of the cementing processes is given by Nelson & Guillot.[14]

The key geometrical factor in the annular displacement is the width of the annular gap and its uniformity. Partly this is influenced by use of *centralizers*, discussed below, which may reduce eccentricity but also constrict locally, and partly by geological factors. The latter can related to weak formation or casing/pipe connection locations along the well, where there may be washed out sections of the annulus, i.e. enlargements or *washouts*. Finally, according to the geomechanical stresses and wellbore orientation the borehole may have an elliptical cross-section, rather than circular.

The challenge of primary cementing is easily understood by anyone who has cemented garden paving stones into place or grouted large floor tiles. The annular space in the well is generally eccentric, meaning that to get good coverage of cement (full removal of the mud) we need to remove the drilling mud from an annular gap that may be e.g. 5mm wide in the narrow part of the annulus, pushing the cement slurry into the gap. Not only is the gap potentially narrow, but it also extends for many 100's of metres - unlike the floor tile/garden paver analogy. This is extremely difficult to achieve and over the years considerable effort has been expended to model/simulate the process in order to improve fluid designs. The model used in this work is comprehensively derived by Bittleston *et al.*,[1] although we in fact

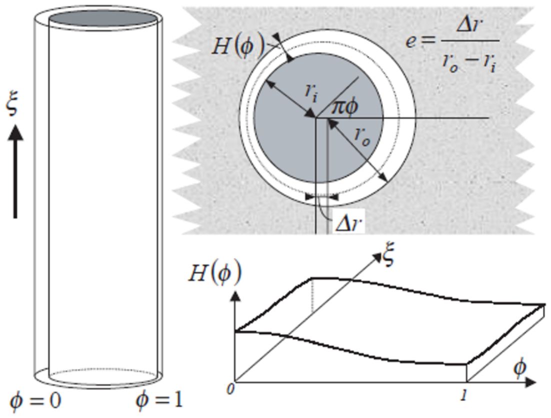

Figure 1. Uniform eccentric wellbore unwrapped into a Hell-Shaw cell. Schematic from.[15]

use a modified version.[9] The fluid-fluid displacement problem is simplified from the full Navier-Stokes equations. The derivation uses standard scaling arguments to simplify the momentum balances and the radial dependency is then averaged along the thickness of the annulus, resulting in a two-dimensional model of the bulk fluid motions in azimuthal (ϕ) and axial (ξ) directions. The narrow annulus formed by the space between the formation and the casing is conceptually unwrapped, resembling a Hele-Shaw cell with varying gap width $H(\phi)$ (see Fig.1). The reduced model consists of a series of first-order conservation equations, for each fluid concentrations pumped, and a quasi-linear Poisson-type equation for the stream function, driven by the pump flow rate and by buoyancy gradients. Rheological effects enter into the nonlinearity of the stream funcion equation.

The model that we use has been studied both analytically and computationally, as well as being used in various industrial case studies. For uniform wells the dynamics of displacement are becoming well understood, as reviewed in the next section. If the well is irregular however, there is relatively little study. Some of the earliest experimental studies considered the effects of sudden expansions on the annular geometry.[2,22] The danger of sudden expansions is to trap drilling fluid, due to its yield stress. Most relevant scientific studies of the fluid mechanics concern single phase flows. Mitsoulis and coworkers[11] studied both planar and axisymmetric expansion flows with yield stress fluids, showing significant regions of static fluid in the corner after the expansion. This was studied further in expansion-contraction geometries, both experimentally and computationally.[4,12,13] Roustaei & Frigaard[18] studied large amplitude wavy walled channel flows numerically, predicting the onset of stationary fluid regions. A more comprehensive study of geometrical variation[20] showed that yield stress fluid becomes trapped in sharp corners and in the small scale features of the washout walls, as well as filling the deepest parts of the washout as the depth is increased. For sufficiently large yield stress and deep washouts, the actual washout geometry has little effect on the amount of fluid that is mobilized: the flowing fluid "self-selects" its flowing geometry. Considering the effects of (laminar) inertia,[19] increasing the Reynolds numbers can result in a reduction in flowing area, i.e. contrary to the industrial intuition that pumping faster is better. Very recently[17] we have been exploring the effects of washout-type irregularity in near-horizontal wells, using a combination of model simulations and lab scale experiments, performed collaboratively.

Here we focus on regular boreholes and explore the effects of varying eccentricity along the well. Eccentricity is controlled via the use of centralizers, which are devices fitted to the outer wall of the casing, designed to exert normal forces when in contact with the borehole wall. A range of centralizers exist and there is no standard geometry/mechanical design. These may be fitted every $9-40$m along the well. The effectiveness of centralization can be inferred from logging measurements taken after the cement job. Positioning of centralizers is designed using a range of models; see Gorokhova *et al.*[5] for the state-of-the art. It may seem surprising that even in a vertical section of wellbore the annulus is not fully concentric: the lowest parts of the casing are in

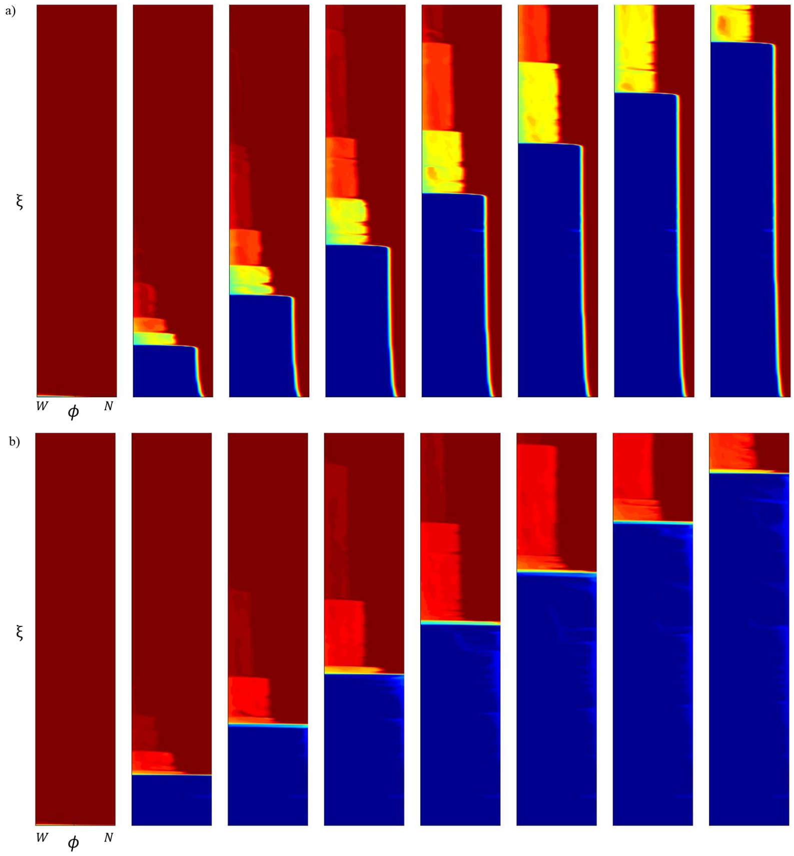

Figure 2. Colourmaps showing the progression of two uniform eccentric annular displacements ($e = 0.3$): a) $\tau_{y1} = 20$Pa, $\rho_2 = 1600$kg/m^3; b) $\tau_{y1} = 20$Pa, $\rho_2 = 1700$kg/m^3. The length of annulus shown is 500m and time intervals are regularly spaced; W and N denote wide and narrow sides.

compression and the higher parts are in tension. Guillot *et al.*[6] review current practices, exploring 2 case studies with vertical well sections of around 500m. In both cases the vertical sections, despite frequent spacing of centralisers, show large scale variation in eccentricity (both predicted and measured).

We base our study on a vertical well of length, $L = 500$m, outer and inner radii, $r_o = 0.1122$m & $r_i = 0.0889$m (≈ 9 & 7 inches). We fix the flow rate to give a mean velocity of $w = 0.333$m/s (laminar flows only). The axial coordinate, ξ, is measured from the bottom of the well. Half of the annulus is modelled, (assuming symmetry about the wide and narrow sides). The azimuthal coordinate ϕ ranges from wide side (W: $\phi = 0$) to narrow side (N: $\phi = 1$).

DISPLACEMENTS IN UNIFORM WELLS

To illustrate the simplest situations we present results of 8 simulations: 2 sets of displaced fluid yield stress, 2 density differences and 2 uniform eccentricities ($e = 0.3,\ 0.6$). The displaced fluid 1 (mud) has fixed properties: $\rho_1 = 1500$kg/m^3, $K_1 = 0.1$Pa.s^{n_1}, $n_1 = 0.5$. We consider 2 yield stresses: $\tau_{y1} = 10,\ 20$Pa. The displacing fluid 2 (pre-flush or cement slurry) has fixed rheological properties ($K_2 = 0.04$Pa.s, $n_2 = 1$, $\tau_{y1} = 5$Pa) and we consider 2 densities $\rho_2 = 1600,\ 1700$kg/m^3.

Figure 2 shows two computed displacement flows in a modest eccentricity well ($e = 0.3$) with high yield stress mud. Initially the annulus is filled with the displaced fluid (red) representing the mud, then, the displacing fluid (blue) is

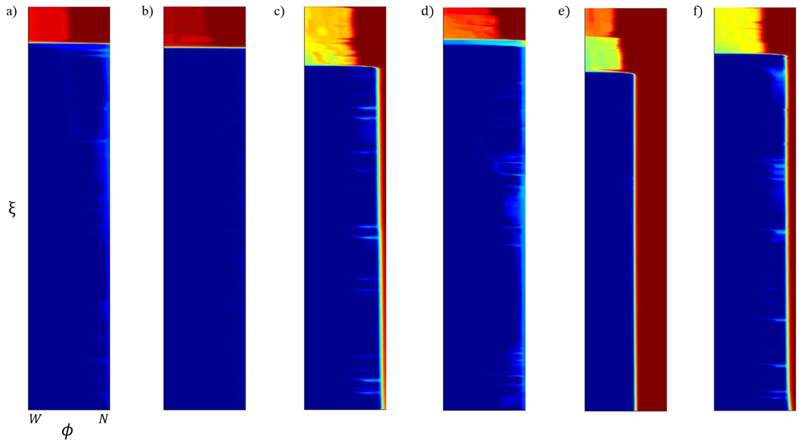

Figure 3. Mud displacement for uniform wells: a) $e = 0.3$, $\tau_{y1} = 10$Pa, $\rho_2 = 1600$kg/m^3; b) $e = 0.3$, $\tau_{y1} = 10$Pa, $\rho_2 = 1700$kg/m^3; c) $e = 0.6$, $\tau_{y1} = 10$Pa, $\rho_2 = 1600$kg/m^3; d) $e = 0.6$, $\tau_{y1} = 10$Pa, $\rho_2 = 1700$kg/m^3; e) $e = 0.6$, $\tau_{y1} = 20$Pa, $\rho_2 = 1600$kg/m^3; f) $e = 0.6$, $\tau_{y1} = 20$Pa, $\rho_2 = 1700$kg/m^3. Each snapshot is taken near the end of the displacement.

pumped at a constant flow rate from the bottom. The snapshots are taken at different time intervals, regularly spaced throughout the passage of the front along the well. Particularly in Fig. 2a (with low density difference), the displacing fluid advances mainly in the wide side of the annulus, leaving behind a uniform mud layer in the narrow side. Strategies to avoid this type of unyielded zone in vertical wells have been widely studied since the 1960's[3,7,8,10,21] culminating in rule-based design systems that can be improved further with models such as that used here.[16] It is generally accepted that a positive density difference in vertical wells, aids to stabilize the interface preventing the formation of a mud channel in the narrow side. On increasing the fluids' density difference (see Fig. 2b), the displacement front is flat and removes the narrow side mud much more effectively. Careful inspection however shows that the mud removal is not complete: residual mud partially contaminates the displacing fluid. Note too that secondary flows before/after the advancing front are responsible for dispersing the preflush ahead of the main front.

For the other 6 displacement flows we plot only a single snapshot, taken as the displacement front nears the top of the annulus; see Fig. 3. In terms of rheology, the mud's yield stress determines the quality of the displacement on the narrow side of the annulus to a large degree, e.g. without a yield stress the static mud channel cannot form. For the smaller yield stress ($\tau_{y1} = 10$Pa) with $e = 0.3$, the displacements are largely effective; see Fig. 3a & b. In Fig. 3a there remains some mixed fluid on the narrow side, comparable to Fig. 2b, illustrating the competition between positive density difference and adverse rheological differences.

When the eccentricity increases (Fig. 3c-f) a bigger density difference is required to effectively displace the mud. Comparing either Fig. 3c with Fig. 3a, or Fig. 3f with Fig. 2b, we see that we have a mud channel at $e = 0.6$, but none at $e = 0.3$. Equally, comparing Fig.2a with Fig. 3e we see the size of mud channel grows significantly with eccentricity.

Although most of the displacements shown result in poor/incomplete mud removal, the physical trends are clear: smaller eccentricty and yield stress, or larger density difference, all result in better displacements. The conditions under which unsteady/steady displacements and mud channels can arise are formally derived in.[16]

DISPLACEMENTS IN IRREGULAR WELLS

To study a effects of irregularity comparatively we have constructed an annular geometry with a 300m long irregular section. The deepest 50m and the top 150m are uniform (see Fig.4). In between we construct a sinusoidal variation in eccentricity with amplitude ± 0.2 about fixed values $e = 0.3$ and $e = 0.6$ for the uniform sections, as illustrated. A total of 10 centralizers are placed between the two uniform sections. The distance between centralizers is 30m. In an ideal situation, the centralizer would achieve 100% standoff ($e = 0$), but under field circumstances this is less likely. Here we assume a constant $e = e_{min}$ over the length of the centralizer (here 40cm).

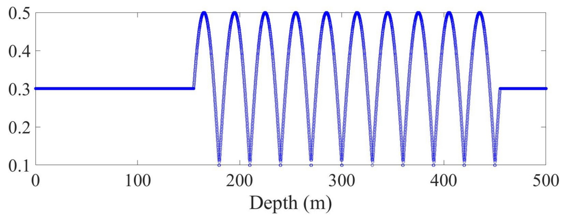

Figure 4. Eccentricity vs. depth: proposed shape for irregular wells; here $e = 0.3$ is the uniform value.

The same 8 displacement flows are run for the irregular geometries as for the uniform annuli (i.e. 2 densities, 2 yield stresses and 2 uniform eccentricities). Fig. 5 shows the fluid concentrations near the end of the displacements for $e = 0.3$. Overall, a good displacement is achieved in Fig. 5a, with reasonable removal in the uniform sections (comparable to Fig. 3a), but larger patches of mixed fluid located at the points of maximum eccentricity, in the narrow side of the annulus. On increasing the mud yield stress in Fig. 5b, these zones grow substantially, retaining static mud on the narrow side in patches that clearly follow the eccentricity variation. This compares with Fig. 2a for the uniform annulus. The width of static channel in the uniform section is very close in both simulations. For the irregular section, there is more residual mud, but the mud channel is broken periodically at the centralizer positions, which could isolate zones better than the uniform mud channel (although here the removal of the narrow side mud and zonal isolation is clearly precarious).

As seen in the uniform cases, increasing the density difference results in a better displacement. Fig. 5c & d show the displacement under same conditions as in Fig. 5 a & b but with the larger density difference. The mud is now removed more effectively, resulting in no mud channel, but still there are patches of contaminated displacing fluid.

The higher eccentricity irregular wellbore is evaluated in Fig. 6 for the same parameters presented in Fig. 5c-f. The eccentricity now varies from $e_{min} = 0.4$ to $e_{max} = 0.8$. In this case, there is residual mud in every case (Fig. 6 a-d). Again it appears that the mud channels are wider than for the uniform annuli, but potentially may achieve partial isolation Notice that increasing the yield stress (Fig.6b) makes the displacement of the mud, even at the centralizer's position (e_{min}), quite challenging. In this particular scenario, when the centralizer does not position the casing to give eccentricity $e < e_{min} = 0.4$, the resulting mud channel is about the same width as that produced in the uniform case without centralization (Fig.3e). Again, on increasing the density difference in Fig.6c & d, the displacement is improved and the residual mud is significantly reduced.

A HELICAL DISPLACEMENT

So far we have studied the effect of an irregular sinusoidal eccentricity along the well. The level of eccentricity changes at different depths while the position of the narrow side is kept fixed. Particularly in a vertical well, the azimuthal position of the narrow and wide side of the casing will not be fixed. Just for a preliminary exploration of this type of effect we have modified our uniform geometry such that the position of the wide side rotates 4 times around the wellbore over the 500m length. Thus, we have a helical eccentric pathway along the well. We now also perform the computations over a full annulus using periodicity conditions in ϕ.

Due to space limitations only a single exam-

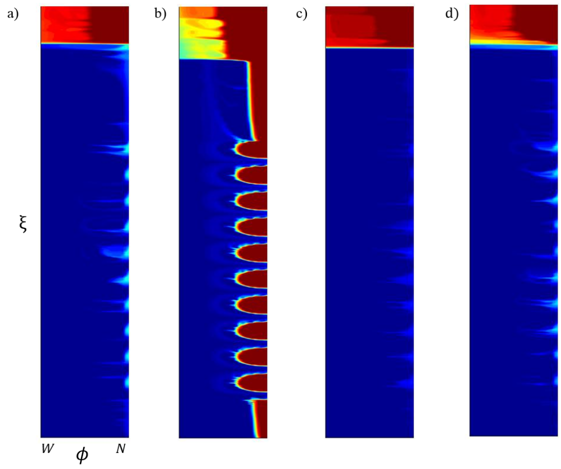

Figure 5. Mud displacement in the irregular annulus with $e = 0.3 \pm 0.2$: a) $\tau_{y1} = 10$Pa, $\rho_2 = 1600$kg/m^3; b) $\tau_{y1} = 20$Pa, $\rho_2 = 1600$kg/m^3; c) $\tau_{y1} = 10$Pa, $\rho_2 = 1700$kg/m^3; d) $\tau_{y1} = 20$Pa, $\rho_2 = 1700$kg/m^3.

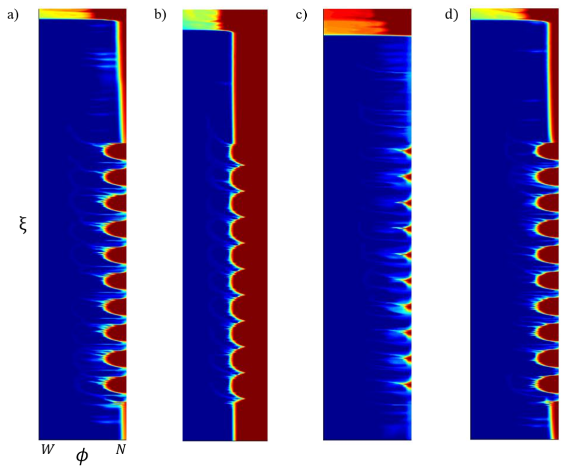

Figure 6. Mud displacement in the irregular annulus with $e = 0.6 \pm 0.2$: a) $\tau_{y1} = 10$Pa, $\rho_2 = 1600$kg/m^3; b) $\tau_{y1} = 20$Pa, $\rho_2 = 1600$kg/m^3; c) $\tau_{y1} = 10$Pa, $\rho_2 = 1700$kg/m^3; d) $\tau_{y1} = 20$Pa, $\rho_2 = 1700$kg/m^3.

ple is shown, as an appetizer to the complexities that will arise in a more complete study to follow. Figure 7 shows a laminar displacement of two Newtonian fluids with identical viscosity (0.01 *Pa.s*) and density (1100 kg/m^3) along the helical channel (with $e = 0.3$). As the fluids are identical here, this is simply a dispersion example. The helical motion of the fluids is evident and the revolving eccentricity appears to result in secondary flows that improve the displacement over that expected in a uniform annulus. It can be expected that more complex rheolgies and the introduction of yield stress will lead to unyielded zones and more difficult displacements.

CONCLUSIONS

We have given an overview of recent studies on fluid-fluid displacement in a long thin annu-

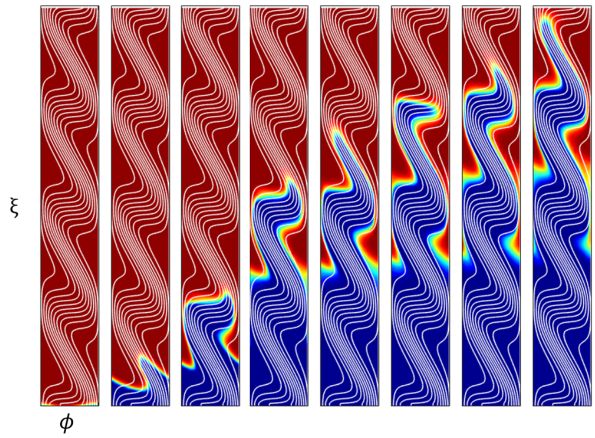

Figure 7. Mud displacement for irregular well with helical geometry: $\rho_1 = \rho_2 = 1100\ kg/m^3$, $K_1 = K_2 = 0.01$, $n_1 = n_2 = 1$, $\tau_{y1} = \tau_{y2} = 0\ Pa$.

lus, covering uniform and irregular geometries. In nominally vertical wells, increasing the density difference in eccentric wells aids the displacement in both, uniform and irregular geometries. However, in presence of a sufficiently high yield stress, neither the use of centralizers nor moderate density difference can prevent the development of a mud channel. The wellbore irregularity leads to a corresponding patterning of narrow side mud channels, which may in marginal cases give a degree of zonal isolation not present in uniform annuli.

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