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# Plug Cementing: A Puzzle for Rheology and Flow

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## ABSTRACT

Plug cementing is an operation carried out in oil and gas wells, in which a cement slurry is placed inside the well, either during construction or later when the well is to be abandoned at end of life. The main idea is that the cement should set where placed in the well and harden to provide a permanent plug. In the case of well abandonment, the plug should also hydraulically seal the well. Since the cement slurry typically has a density $1.7 - 1.9$ SG and the underlying fluid is often water, there is a strong likelihood of Rayleigh-Taylor and other buoyancy driven flows emerging. Although the cement slurry has a yield stress ($1 - 10$ Pa), it should also be pumpable and retarders are often used to delay thickening. Thus, it is questionable if the slurry yield stress is large enough to prevent motion. Indeed, it is somewhat magical that the cement can stay in place while it sets, as is apparently the case. How does this work? Here we outline some of the approaches taken to studying this mystery and present results of our ongoing research.

## PLUG CEMENTING

Cement plugs are placed in most oil and gas wells, at abandonment if not during construction. Abandonment refers to the decommissioning phase of an oil well's life, where the well operator is typically obliged to seal the well hydraulically to mitigate risks of future leakage. In Western Canada there are $> 500,000$ oil and gas wells. At end-of-life, production wells are generally washed clean with freshwater, both to remove corrosive liquids and to improve wetting contact of the cement slurry with the inside of the steel casing. The cement slurry is then pumped into the well at the desired depth, with a volume that can typically correspond to $15 - 200$m of the well length.[1] Both mechanical seals (bridge plugs) and cement are used to seal the well. It is also possible to place a support device in the well under the pumped slurry, although this is not always done. Here we focus on the interesting question of placing a heavy cement slurry above a less dense fluid (water) and the obvious question of whether the cement slurry can remain stably *off-bottom*, at least for sufficient time to thicken.

Plug cementing can be conceptually divided into 3 stages. First, tubing is run into the well, to the depth where the plug is to be placed, and pumping commences. For off-bottom plugs there is an immediate question of whether the pumped slurry turns around and flows up the well. Alternatively it may flow down the well, exchanging place with the water underneath, or something in between these possibilities. The pumping phase has been studied recently using computational tools.[2–4] The evidence is that, given sufficient flow rate, the stream of pumped slurry eventually destabilizes and mixes with the water locally. This allows the fresh cement to turnaround and flow upwards in the well. There have also been a number of recent experimental studies of placement fluid mechanics in the closely related process of dump-bailing.[5–8]

In the second stage, the tubing is slowly extracted from the cement slurry, often using some variant of what is called the balanced plug method.[9] The pulling speed is kept slow to allow for the equilibration of heights (pressures) between the tubing interior and surrounding annulus. This is to minimize mixing as the tubing exits the top of the plug. At the lower interface, recent results suggest that pulling out does not significantly disturb the bottom interface once the tubing is more than a few diameters above interface position.[10]

The third stage is to consider what happens after the tubing has been withdrawn and the pumps are turned off. A likely scenario is to have some degree of mixing at the lower interface of the plug, which may modify the effects of the density unstable buoyancy gradient. Given the wide range of tubing end-pieces used, different geometrical configurations (e.g. likely eccentric in the well), and different slurry properties, it is hard to specify the *initial* configuration of the slurry-water mix, at the time when the pumps are turned off. In this paper we focus on this 3rd stage of the process and the question of how the plug may remain in place.

## POST PUMPING STABILITY

In the absence of any resistance to fluid motion and of mixing, we can estimate a speed of failure of a "ball" of slurry of size $\sim \hat{D}$: the diameter of the well. The dense cement ball creates buoyancy stresses of size $\sim (\hat{\rho}_C - \hat{\rho}_W)\hat{g}\hat{D}$, where $\hat{\rho}_C$ and $\hat{\rho}_W$ are respectively, the densities of cement and water. These stresses will lead to acceleration of the underlying fluid. If the ball falls steadily, the buoyancy stresses must be balanced by either inertial or viscous stresses, but the latter are generally smaller for water. Hence we have a balance:

$$(\hat{\rho}_C - \hat{\rho}_W)\hat{g}\hat{D} \sim \hat{\rho}_W \hat{W}_f^2 \quad \Rightarrow \quad \hat{W}_f = \sqrt{(\hat{\rho}_C/\hat{\rho}_W - 1)\hat{g}\hat{D}}, \tag{1}$$

giving an order of magnitude for the speed of failure $\hat{W}_f$. For typical cements and wells, $\hat{W}_f \approx 0.2-0.5$ m/s. For a plug length $\hat{L}_{plug} \sim 10-100$ m, the failure time is $1-10$ minutes, which is too fast for the cement to thicken and set. In other words, other mechanisms must be at play in order to keep the cement plug stable. We explore 3 different potential scenarios.

### Scenario 1

In scenario 1, we assume that rheology plays a dominant role. In the absence of any motion, viscous and inertial stresses in the fluids should be zero. This implies that in a *static* configuration the buoyancy stresses can only be balanced by the yield stress of the fluids. Note that we neglect surface tension effects as typically wells are large ($\hat{D} \geq 0.15$ m) and cement-water are miscible, although for other systems this could be significant. The question of how large the yield stresses need to be in order to prevent axial slumping motions of the fluids from developing has been extensively studied,[11–13] leading to stability criterion,[14,15] that are described in terms of the inclination of the well $\beta$ and limits on 2 the dimensionless yield stresses:

$$\tau_C = \frac{\hat{\tau}_{C,Y}}{(\hat{\rho}_C - \hat{\rho}_W)\hat{g}\hat{D}}, \qquad \tau_W = \frac{\hat{\tau}_{W,Y}}{(\hat{\rho}_C - \hat{\rho}_W)\hat{g}\hat{D}}, \tag{2}$$

where $\hat{\tau}_{C,Y}$ is the yield stress of the cement slurry and $\hat{\tau}_{W,Y}$ that of the underlying fluid. Here we have $\hat{\tau}_{C,Y} = 0$, for water, and we consider vertical wells $\beta = 0$. Axial motions will be prevented[14,15] provided that

$$\tau_C = \frac{\hat{\tau}_{C,Y}}{(\hat{\rho}_C - \hat{\rho}_W)\hat{g}\hat{D}} \geq 0.3043. \tag{3}$$

For $\hat{D} = 0.15$ m, and $(\hat{\rho}_C - \hat{\rho}_W) = 800$ kg/m$^3$, this requires $\hat{\tau}_{C,Y} \geq 360$ Pa. While these stability estimates may be a bit conservative, even $\hat{\tau}_{C,Y} \sim 100$ Pa is an order of magnitude larger than typical yield stresses found in cement slurries $(1 - 10$ Pa), and would lead to questions of pump-ability. Although this means that the stability criterion[14,15] are typically not met by pumped slurries, it is worth noting that cement slurries do develop static gel strengths within this range, typically within $40-90$ minutes (or longer depending on retarders used). Indeed industry procedures are in place that consider thickening times in downhole conditions systematically, as part of the design. In other words, if the top of the cement plug is not disturbed before it thickens, rheologically the slurry can support itself.

## Scenario 2

In scenario 2, as cement and water are miscible, one might hypothesize a mixed region of length $\hat{L}_{mix}$ that arises during pumping. Although we have no way of determining $\hat{L}_{mix}$, we may question whether the flow can remain stable? To our knowledge this has not been analysed in any depth. Two approaches seem sensible. First, one neglect the yield stress of the cement and treat this as 2 Newtonian fluids evenly mixed. The situation is akin to a Rayleigh-Bénard problem, with fluid concentration taking the place of temperature, adopting the usual Boussinesqu approximation and performing a linear stability analysis, under suitable simplifying assumptions. The task then is to interpret the results in the non-Newtonian context. Note that including a finite yield stress makes such analyses linearly stable, from an energy stability perspective.[16]

In the second approach, one might instead make an order of magnitude estimates that include the yield stress. In the first place, lets assume that a criterion similar to Eq. 3 governs the static stability, as should be true on dimensional grounds. Instead, we assume that the buoyancy stress is over-estimated in the case where we have a mixed region of length $\hat{L}_{mix}$. As the pipe diameter limits the size of any perturbation from the stratified mixture, we might assume that any density difference in the mixed region has maximal size $\Delta\hat{\rho}_{mix} \approx [(\hat{\rho}_C - \hat{\rho}_W)/\hat{L}_{mix}] \times \hat{D}$. Consequently, the buoyancy stress has a maximum size $\Delta\hat{\rho}_{mix}\hat{g}\hat{D}$, and now we might replace Eq. 3 by:

$$\frac{\hat{\tau}_{C,Y}\hat{L}_{mix}}{(\hat{\rho}_C - \hat{\rho}_W)\hat{g}\hat{D}^2} \geq \tau_{critical}. \tag{4}$$

The critical value $\tau_{critical}$ is not known, but we might assume it is of similar numerical size to Eq. 3, i.e. $\sim O(0.1)$. We see that the effect of the mixed zone is to reduce the required cement yield stress by a factor proportional to $\hat{D}/\hat{L}_{mix}$: effective mixing over a length of $2-5$m could result in reduced buoyancy stresses, to a size that typical cement yield stresses can stabilise.

The above two analyses for scenario 2 are both somewhat crude. They neglect unknown effects of cement-water mixing and assume a uniform density stratification, when in practice there is no distinct "break" between plug placement stages and no reason for there to exist any such background distribution of density. Lower in the well, where the water to cement ratio is higher, the Newtonian viscous analysis may be more valid. Similarly, where the cement concentration is highest the modified static stability estimates (Eq. 4) may be representative. Despite these concerns, we feel the 2 approaches have value as conceptual analyses with which to build a broader framework of understanding of plug stability mechanisms.

### Scenario 3

The third scenario we consider acknowledges the failure of Eq. 3 for typical off-bottom placement. In scenario 3 the fluids move. The questions to be answered are: how do the fluids move and can we estimate timescales of motion. If these timescales are sufficiently long, then the upper part of the plug can remain intact. This flow has been studied experimentally in the laboratory setting by 2 groups,[17−18] each using Carbopol as the yield stress fluid and visualizing the flows. In terms of the questions, both studies can only be regarded as offering preliminary insights.

Vargas *et al.* used low density oils underneath Carbopol, weighted with glycerin.[17] Many examples of flow morphology are shown, with typically the heavy Carbopol moving centrally down into the fluid below. This motion can be either as a stable (near-uniform) plug-like motion, displacing fluids upwards around the walls, or as wavy core annular stream that could destabilize. They present their results in terms of a dimensionless terminal velocity that is effectively scaled with our $\hat{W}_f$ from earlier, (except with inertial stress normalised with $\hat{\rho}_C$). These velocities are order 1 and decrease to zero as $\tau_C$ crosses a threshold, of around 0.1, indicating some conservativeness in Eq. 3. There may also be contributing viscous effects here as the oils are 50-100 more viscous than water.

Vogl *et al.* used water underneath Carbopol, weighted with sugar solution.[18] Interestingly here, the heavy fluid descended around the walls while the water penetrated upwards, typically in a finger that was near symmetric. The wall layers developed waves and generally pieces of the Carbopol would detach from the wall film and fall more rapidly down through the water. In a few cases the exchange flow morphology was not core-annular, but side-to-side. Also for large enough $\tau_C$ the flows were stable, but the number of experiments is small. Comparing these two studies, we can speculate that the distinctly different morphologies may have something to do with both wetting of the wall by the oil, hence being difficult to displace.[17] The only other difference is really in terms of viscosity of the underlying fluid.

## ONGOING WORK

Our current work continues in extending the study of Vogl *et al.*[18] to a wider range of parameters, so that the propagating finger velocity can be estimated. At the same time, we are exploring some of the stability questions raised above.

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