Project Profile

Project Name:	Fluid Mechanic Causes of Gas Migration
Project Number:	EI-2016-09
Proponent:	Department of Mechanical Engineering, University of British Columbia
Funding Envelope:	Environmental Impacts
Timeframe:	October 1, 2015 to September 30, 2016

Project objectives

The overall objectives are to better understand some of the underlying causes of gas migration and how situations in which gas migration occurs can be avoided. Objectives for the individual 3 parts of the project, (as described below), are as follows:

Micro-annulus formation and prevention during cement placement: we intend to model the displacement process using specially developed computational fluid dynamics codes and analysis, to determine fluid properties and flow conditions that avoid micro-annulus formation.

Fluid invasion into a gelled column: we intend to study the mechanisms by which fluid invades a static vertical column of gelled fluid. In particular, we will try to quantify the effects of the yield stress and the height of the gelled column on the critical pressure overbalance needed for fluid to begin to enter the column.

Cement hydration modelling and predicting pore pressure reduction: To construct a mathematical and computational model of the cement slurry behavior directly following placement in the annulus. The model should include sub-models for: cement hydration, slurry rheology, particle settling/consolidation, multi-phase porous media evolution, heat transfer and contact with a saturated rock formation. This model is targeted at the induction and acceleration phases, lasting say 2-12 hours after placement.

Project description

The project involves 3 parts, to be pursued in the context of an ongoing PhD thesis at UBC and supporting studies.

- ***Micro-annulus formation and prevention during cement placement***

As fluids are circulated around the wellbore in primary cementing a key part of the process involves the removal of drilling mud from the annular space. Usually the cement slurry is preceded by one or more washes/spacer fluids, which are designed to have a rheology and density that aids displacement of the drilling mud. However, due to the yield stress and viscosity of the drilling mud, it is common that a part of the mud is left behind on the walls. These thin layers may connect around the circumference forming a so-called micro-annulus. As the cement slurry sets, these mud layers become de-hydrated, forming porous hydraulic connections longitudinally along the well.

More than 10 dimensionless parameters are involved in modelling the displacement of 2 non-Newtonian fluids with yield stress in a 3D annular geometry. This significantly increases the difficulty of making a comprehensive computational study of any primary cementing flow. Therefore, we take a simplified approach and reduce the number of governing dimensionless parameters, so that we might be able to focus on a problem that is physically relevant and allows us to understand physical mechanisms. First, to reduce the rheological complexity the displaced drilling mud is characterized by the Bingham fluid model, instead of a Herschel Buckley model, and we assume it is displaced by a Newtonian fluid (spacer). This allows us to simplify but still systematically study yield stress effects and viscosity ratio effects. Secondly, we consider a two-dimensional geometry between two parallel plates, which models a longitudinal section of the annulus. We focus then on studying the thickness of residual wall layers in a density-stable miscible displacement, i.e. the denser fluid displaces the lighter fluid in the upwards direction. Study of buoyancy effects and their competition with the yield stress of the drilling mud is the initial focus.

- ***Fluid invasion into a gelled column.***

In order for formation fluids (gas or liquid) to enter the well it is necessary for there to be a pressure imbalance. A pressure imbalance may not however be sufficient for fluids to invade. In the event of the invading fluid being immiscible with the cement slurry, it is firstly also necessary to overcome a capillary pressure limit, which may depend critically on the pore radius or other local geometry. Secondly, the rheology of the cement slurry has an effect on invasion. This fact is widely acknowledged in the industry, where usual API recommendations involve setting a target time for the cement slurry to develop 500 $lbf/100ft^2$ of gel strength. Indeed many slurry additives are targeted at control of gel strength in the semi-solid state. Despite this reliance on gel strength development, there are few detailed studies of the actual invasion process, where a pressure imbalance is resisted by a yield stress fluid. This project seeks to rectify this situation.

The project will commence with a dimensionless analysis, in order to help with experimental design. The main activity will be experimental and will be performed in a specially designed and recently commissioned apparatus. In place of gas, to eliminate buoyancy and capillary effects, we work with aqueous liquids as the invading fluid. The in situ gelled column is Carbopol, a transparent lab fluid that we are experienced with. We will study a range of both column heights and yield stresses, in each case increasing the pressure imbalance slowly until invasion is observed. Once invasion commences, after a short initial period of dome-like penetration, the invading fluid tends to finger through the gel in an unstable and unpredictable fashion. As well as further experiments in this sequence, new experiments with varying viscosity are planned and we may also study micro-sphere suspensions in place of the Carbopol, to understand the effects of suspension microstructure. Once we have sufficient experimental data we also intend to use an in-house CFD code to simulate parts of the invasion pressure.

- ***Cement hydration modelling and predicting pore pressure reduction.***

Finally, we intend to address a long-standing theory concerning fluid invasion during hydration. After pumping, the static slurry passes through the induction into the acceleration phase of hydration, over a period of hours, as influenced by retarders and other additives. Chemically, the rate controlling step concerns hydration of the silicate phases and in particular aelite (denoted C_3S). Despite decades of research it is only fairly recently that a clear picture has been agreed upon for what happens at the micro-scale. In pre-induction C_3S reacts with water to form a thin layer of metastable C-S-H(m), around each cement grain. In induction the C-S-H(m) dissolves from the outside of unreacted cement grains while at the same time forming on the inside through fresh reaction, controlled by slow flux of water (H) through the protective layer . The dissolving C-S-H saturates the surrounding solute and precipitates into a stable C-S-H(s) gel and CH (limestone). This stage is auto-catalytic, in that the number of precipitation sites grows, and leads to the acceleration phase. Similarly complex, but less critical, reactions take place with the aluminate phases.

During the hydration, as above, it is the C-S-H(s) & CH combination that is primarily responsible for the growth of gel strength within the slurry. There is an accompanying net shrinkage of volume (chemical and potentially from leakage), so that the slurry settles downwards in the annular space very marginally as the gel strength increases. Conceptually, the gel strength acts to oppose the settling, resulting in a net reduction in static pressure in the cement column. It is supposed that this pressure reduction (at the bulk scale) allows the pressure imbalance necessary for fluid to invade. On a more microscopic scale, one supposes that the growth of structural strength in the solid phase of the slurry during hydration allows for a reduction in pore pressure, and eventually to invasion.

In order to test some of these theories it is necessary to be able to quantify evolution of the solid and liquid phases during the hydration process in the well. Also happening on the same timescale can be other more fluid mechanics processes that are also important to eventual well integrity, e.g. settling of the solid phase (particularly in horizontal wells). This is a challenging area in that no comprehensive models exist targeted at well cementing. On the other hand, models for slurry rheology, settling/consolidation, cement chemistry and evolution of reacting porous media are all individually well advanced in the scientific literature. Thus, the challenge is to combine these models in a pragmatic way that allows for process-level model-based analysis to be conducted.

Project background

A significant % of oil & gas wells leak, allowing gas and subsurface fluids to migrate to surface. This is despite >80 years of worldwide experience in primary cementing of oil & gas wells, together with significant evolution of industry no-how, equipment and materials. Leakage is common in Western Canada and presents both environmental and health/safety risks, as well as reducing well productivity. Key reasons for the failure of the industry to solve this problem include both managerial/operational factors and the wide range of different potential physical causes. This project proposes an in depth study of those physical causes related to fluid mechanic issues, with the aim of improving physical understanding in the industry.

Project approach

The project will be carried out using a mix of analytical, computational and experimental techniques, as have been discussed above.

Project deliverables

The deliverables from this project include the following:

1. Annual Report.
2. Presentation to the sponsors.

The other main deliverables will consist of contributions to the open scientific literature in each of the outlined areas, in the form of both scientific journal papers and conference presentations. The results will provide an independent assessment of the rationale for some aspects of current primary cementing operations. The net result of all of these will be a PhD thesis.