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Development of simulations based correlations to predict the cement volume fraction in annular geometries after fluid displacements during primary cementing

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ABSTRACT

Primary cementing involves the Newtonian and non-Newtonian fluid displacements. In this process cement replaces mud in the casing-formation annulus. The spacer fluids are used as a buffer between mud and cement and help in displacing mud as well. Once set cement acts as a barrier for zonal isolation. In an ideal cement job 100% of annular volume is occupied by cement. In this study a computational fluid dynamics (CFD) model is used for a 50 ft virtual well model section. It is initially filled with mud and subsequently swept by one annular volume of spacer followed by one annular volume of cement. The performance of mud displacement process under varying conditions of spacer density, viscosity and displacement rates is studied. Temporal variation of the mud volume fraction in different axial sections is used to monitor the efficiency of displacement process and behavior of fluids involved. Based on these simulation results, a correlation is developed to predict the final cement volume fraction in the annulus for the given operating conditions. The results of this study will help in better understanding the complex flow physics involved in the combination of Non-Newtonian and Newtonian fluid displacements.

1. Introduction

Effective zonal isolation during primary cementing can only be achieved, when drilling mud in the annulus is completely replaced with the cement. Sometimes due to their chemical incompatibility mud and cement are to be physically separated and in the annulus this can only be achieved by pumping some other fluids in between them. Spacer fluids are used as a buffer between mud and cement and they also aid in removing mud from the annulus as well. Incomplete mud removal may result in a bad cementing job with poor bonding at cement-casing or cement-formation interfaces. In worst case scenarios, a continuous mud channel may exist in the annulus, which may allow different zones behind the casing to communicate with each other and thus failing the main aim of placing the primary cement.

Due to its critical importance in primary cementing, mud displacement process has been a topic of interest for such a long time in the well cementing community. Some key factors influencing primary cement job failures were identified, and solution were proposed as early as 1940, Jones and Berdine (1940). The parameters influencing the primary cementing process are conditioning of drilling fluid (gel strengths), casing vs. hole size (annular cement sheath thickness), casing centralization/standoff (eccentricity), pipe movement (reciprocation and/or rotation), flow rates, formation permeability, density difference between displacing and displaced fluid, spacer design and contact time.

Using a large scale simulator, Jones and Berdine (1940) showed that poor zonal isolation could be attributed to channeling of the cement slurry through the mud. Contact between the drilling mud and cement slurry often results in the formation of an unpumpable viscous mass at the cement/drilling mud interface (Smith, 1984; Sauer, 1987). Spacer fluids compatible with both the cement slurry and drilling mud are used to serve as a mud removal aid and as a buffer between the well fluids and the cement slurry (Kettl et al., 1993). For wells where oil based muds have been used, the added concern of leaving the casing and formation in a water-wet condition must also be addressed. In vertical wells, past research has shown that a minimum of 8–10 min of spacer contact time at the maximum rate possible should be planned for (Sauer, 1987; Smith and Ravi, 1991). Vefring et al. (1997) presented an

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Abbreviations/Symbols: D_o, borehole diameter (OD for annulus); D_i, casing outer diameter (ID for annulus); ρ_s, density of spacer; ρ_m, density of mud; ρ_c, density of cement; Re_c, Reynolds number cement; τ, time for one annular sweep; μ_s, viscosity of spacer; μ_m, viscosity of mud; μ_c, viscosity of cement; μ_p, plastic viscosity; τ_y, yield stress; CFD, computational fluid dynamics; VOF, volume of fluid; Cp, Centipoise

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optimization study for primary cement placement using computational fluid dynamics (CFD) approach and demonstrated the potential of such simulations for fluid displacement processes. Guillot et al. (2007) studied the efficiency of various preflushes in displacing mud. They found that, preflushes may not be as effective as they are thought of in preventing direct contact between the drilling fluid and the cement slurry, even when industry accepted rules are used to design these preflushes.

Moran and Savery (2007) presented annular velocity data for a variety of eccentric annulus configurations and highlighted several unexpected observations (referred as swap phenomenon). A need for rigorous mathematical model for cement placement that can resolve the annular regions and flow instabilities in time dependent fashion was advocated. Further, contact time for cement and formation in horizontal wells may need to be increased if any settled solids or excessive eccentricity is expected. Moran and Savery (2007) developed a 3-D, two phase CFD simulator and showed the effect of eccentricity and pipe rotation on the moving interface between two fluids and found that casing rotation helps in having good cement on narrow side as well. Moroni et al. (2009) presented a model to account for the pipe rotation effects during the hole cleaning and cement placement process and showed the improvement in cement slurry placement predictions matched well with the field cement bond logs.

The instability of the interface between two superposed Newtonian fluids of different densities at rest was initially studied by Rayleigh (1882). Taylor (1950) included the effect of a constant acceleration acting perpendicularly to the interface and concluded that if the acceleration is directed from the less dense to the denser medium then any slight disturbance to the interface will grow exponentially with time. An interfacial instability also occurs when a more viscous fluid is displaced by the less viscous one, this instability is known as the Saffman–Taylor instability (Saffman and Taylor, 1958). This instability results in the form of finger-shaped intrusions of the displacing fluid into the displaced one and can have significant impact on the efficiency of displacement process. Both of the above mentioned instabilities are involved in the primary cement placement process, by careful selection of the spacer fluid properties the growth of these instabilities can be suppressed. See Sections 5 and 6 for explanation of numerical results that show “apparent” instability around interface that ought to be in the stable fluid displacement regime.

In this research study, a CFD based simulation approach is used to understand the time dependent fluid displacement behavior in a spatially resolved annular domain to represent the physical process of primary cementing between the casing and formation annular region. For given fluid properties of cement and drilling mud, a parametric study is carried out to evaluate the influence of spacer properties and fluid displacement rate on the displacement efficiency of cement placement process. A simulation based correlation is developed to demonstrate the capability and usefulness of CFD methodology for cementing process and its subsequent evaluations. The results of this study will help in better understanding the complex flow physics involved in the combination of Non-Newtonian and Newtonian fluid displacements and selecting the optimal spacer properties with the given properties of cement and mud.

2. Analysis setup

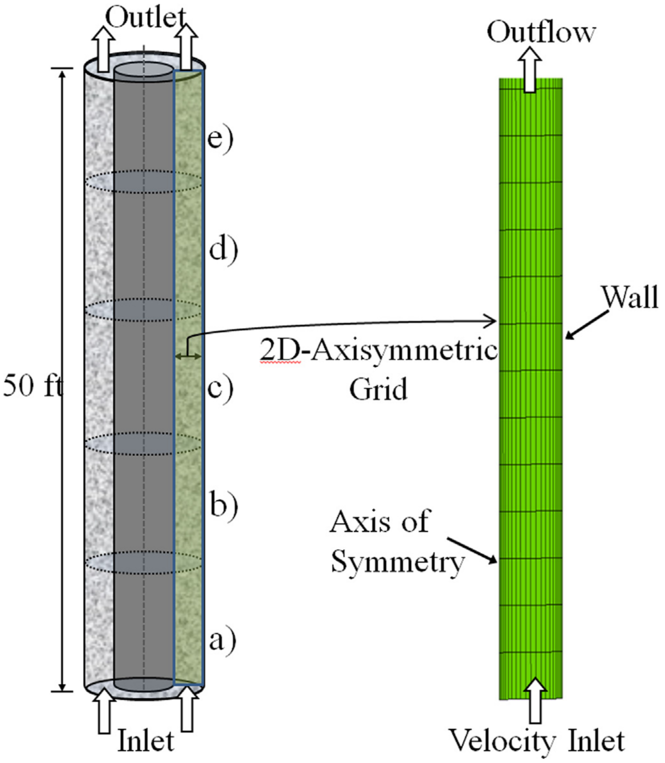

Fig. 1. Schematic of concentric geometry and corresponding 2D-grid, not to the scale.

The virtual well model used for the analysis consists of a 50 ft vertical section of 8.765″ OD × 12.5″ ID annulus. The annulus initially contains the mud and then one annular volume of spacer sweeps through section followed by one annular volume of cement. These fluids enter from the bottom and exits at the top. The 50 ft section is further divided into five subsections of 10 ft length and the fluid volume fractions are averaged for these sections. Each subsection can be inspected individually for number of volume sweeps, either by the spacer or the cement. For example the lowest section (a) will be swept 5 times when either the spacer or the cement sweep once the entire 50 ft annulus. Due to the spatial fluctuations of fluid volume fraction, their area weighted averaged are taken for each of the 10 ft section, instead of monitoring them at a single location, for further details please see Zulqarnain (2012). The top most 10 ft section was selected to observe the time-dependent behavior of fluid displacement under different parametric variations. When this section has satisfactory cementing job, then lower sections would definitely have good cement job as well (Fig. 1).

Mud and cement rheological properties shown in Table 1, are taken from Wilson and Sabins (1988) and are kept constant for all simulations. Mud and cement are treated as Power Law fluids while spacer is a Newtonian fluid. Herschel Bulkley model was considered for eccentric cases and results have been reported in Zulqarnain and Tyagi (2014).

The spacer density, viscosity and displacement rate are varied to achieve the ideal piston like displacement. The spacers are usually lighter than mud and cement, and are Newtonian fluids. Sometimes fresh water is also used as a spacer. The fluid are treated as miscible i.e. no interfacial tension as most of the times all of them are water based. The Reynolds number in these simulations is based on the cement properties and its displacement

Table 1
Mud and cement rheological properties adopted from Wilson and Sabins (1988).

Fluid	Density, ρ (lbm/gal)	Power law exponent (n)	Consistency index K (eq. Cp)
Mud	**13.1**	**0.607**	**1346**
Cement	15.8	0.308	4708