Journal of Petroleum Science and Engineering 126 (2015) 105–123

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

A model for annular displacements of wellbore completion fluids involving casing movement

P.M.J. Tardy [a,*], S.H. Bittleston [b]

[a] Schlumberger, Ares Tower, Donau-City-Strasse 11, 1220 Vienna, Austria
[b] Schlumberger Gould Research, High Cross, Madingley Road, Cambridge CB3 0EL, United Kingdom

ARTICLE INFO

Article history:
Received 13 August 2014
Accepted 11 December 2014
Available online 31 December 2014

Keywords:
cementing
mud circulation
cement coverage
annular flow
Herschel–Bulkley fluid
moving casing

ABSTRACT

This paper presents a mathematical and a numerical model for solving the flow and displacement of completion fluids in the annular space formed by the gap between the outer wall of the casing and the rock face. Such flows occur during mud circulation and cementing operations and may involve casing rotation and reciprocation. Most completion fluids have a shear-dependent apparent viscosity. Additionally, muds and cement slurries often exhibit a yield stress and a gel strength. The displacement patterns and the final placement of the cement depend on injection rate and casing movement histories, rheology contrasts, density contrasts as well as the actual shape and orientation of the annular space which may vary along the wellbore axis. All the above listed phenomena are included in the model. The mathematical model is derived using the lubrication approach and the narrow-slot approximation for the momentum balance equations. These methods provide a $(2+1)$D-averaged model where the radial dimension is not neglected but averaged across the gap. The numerical model is developed in the goal of minimizing computational time. It takes advantage of multiprocessor architectures, first to pre-compute the closure equations linking local flow velocity to local pressure gradient, prior to running the displacement simulation, and second, to solve the non-linear pressure equation by sampling multiple choices of relaxation parameters.

1. Introduction

Cements support and protect well casings and help attain zonal isolation. Failure to accomplish proper cement coverage can result in unsafe, environmentally dangerous, and less profitable wells. The model presented here can help engineers deliver guidelines for ways to control many of the parameters that strongly affect coverage, in the goal of designing more robust cementing jobs. In order to achieve uniform cement coverage, it is important to ensure that no mud is left in the annular space. Indeed, cement may not set along mud channels, and eventually, a path is left behind the casing that the formation fluids may follow. Annular fluid migration may cause loss of produced hydrocarbon into a lower pressure zone, which may or may not be part of the production interval, and hydrocarbon contamination of shallower aquifers. The migration may also cause pressure imbalance between annulus and tubing resulting in pipe deformation or burst and to a blowout at the wellhead.

In order to predict the final distribution of the cement, a model must be able to describe the geometry of the annulus. Typically, the annulus forms a narrow space of varying width. The geometry varies axially due to changes in wellbore and/or casing diameters, and azimuthally due to irregular wellbore shapes and to casing eccentricity. The orientation of the casing eccentricity may be arbitrary and is a result of the distribution of friction along the casing during its descent into the wellbore. Additionally, it is not uncommon to rotate and/or reciprocate the casing in the goal of maximizing mud removal during cementing operations. The shearing motion created by the casing movement may force the mud to yield in places where it would remain gelled otherwise. It may also force the slurry to reach some narrower parts of the gap that would remain unreachable otherwise. The model must also account for the non-Newtonian nature of the completion fluids. Traditionally, such fluids are described as Herschel–Bulkley fluids. Such fluids have a shear-dependent viscosity and may have a yield-stress. The yield-stress is a measure of the wall shear-stress below which the fluid stops flowing and freezes like a solid. Gel strength is also a common feature of these fluids, a measure of the shear-stress that must be exceeded before the fluid starts flowing while initially at rest. The fluids involved in a pumping schedule will have different rheological properties and densities which, even in a regular axisymmetric annulus, may be responsible for complex non-uniform displacement patterns.

Studies of the annular flow of visco-plastic fluids deal with two problem types. The first is relevant to mud circulation, a single-fluid flow problem focusing on the determination of the annular flow field

* Corresponding author.
E-mail address: ptardy@slb.com (P.M.J. Tardy).

http://dx.doi.org/10.1016/j.petrol.2014.12.018
0920-4105/

and friction pressures. In the field, mud circulation is performed to ensure that the mud does not gel and that drilling cuttings are transported to surface prior to pumping the cement slurry. The second deals with mud displacement, a multi-fluid flow problem. Mud displacement occurs as soon as spacers, washes and slurries are pumped. The study of fluid circulation started with a single Bingham fluid in concentric annuli (a sub-class of Herschel–Bulkley fluids) in Fredrickson and Bird (1958) where the flow-rate *vs.* pressure–drop relationship is established. The equation for Herschel–Bulkley fluids was presented in Hanks (1979). Flow profiles for single Bingham fluids were investigated in Walton and Bittleston (1991) using the narrow gap approximation (a.k.a. slot approximation) and in Szabo and Hassager (1992), analytically for asymptotically small eccentricities and numerically otherwise. These studies focused on describing the flow in the plan normal to the casing axis. Casing rotation was introduced in Bittleston and Hassager (1992), again for a single Bingham fluid. In this work, a semi-analytical solution is found when the slot approximation is used and a numerical one is used when the approximation fails. In Escudier et al. (2002), extensive high resolution 2D finite-volume numerical flow calculations of various non-Newtonian fluids (including Herschel–Bulkley fluids) are proposed for eccentric annuli and rotating casings. This work provides a good review of published work on this matter. However the focus remains on friction pressures and not on circulation efficiency. Friction pressures were also investigated experimentally for Herschel–Bulkley fluids in Kelessidis et al. (2011) for both concentric and fully eccentric annuli. Early studies of the displacement problem include that in McLean et al. (1967) with a 1D model based on the sectored concentric annulus analogy for Bingham fluid in eccentric annuli, without gravity. Casing rotation was investigated experimentally and observed to improve mud displacement in eccentric annuli. In Jamot (1974), porous media flow equations are used to model annular flow and to account for buoyancy forces. It is observed that pumping with a denser or more viscous fluid improves displacement efficiency. In Flumerfelt (1975) with power-law fluids, and then in Beirute and Flumerfelt (1977) for Robertson–Stiff fluids, a lubrication-type model is developed to study the displacement of one fluid by another assuming vertical upwards flow without azimuthal flow. While this type of model has the advantage of solving the flow and displacement profile across the gap, it suffers from severe limitations for cases where significant azimuthal flow occurs *e.g.* when fluids have different densities. Additionally, this type of lubrication models significantly over-estimate residual mud layers on the wall as shown in Allouche et al. (2000) and Taghavi et al. (2012). 2D models solving the flow in the axial-azimuthal plan have been proposed and derived using gap-averaged properties with the lubrication approach. Work from Bittleston et al. (2002), Pelipenko and Frigaard (2004b) and Pelipenko and Frigaard (2004a) is similar to Hele–Shaw approach. We will follow this type of modeling here. The annular flow field being essentially 3D in most cases, it is tempting to consider solving the 3D Navier–Stokes equations over the full annulus, coupled with the relevant rheological constitutive equations of the fluids involved. If feasible, such an approach would suffer fewer limitations than other models. 3D Newtonian displacements were considered in Szabo and Hassager (1997), and more recently, 3D non-Newtonian models have been suggested in Savery et al. (2008) and in Zulqarnain (2012). However, these approaches are too restrictive when it comes to simulating the displacement over the full wellbore scale and over typical operation timescales. Such simulations take prohibitively large execution times and are restricted to very coarse meshes which prevent the correct modeling of the displacement in many cases: large shear gradients near the walls, turbulent flows, accurate flow profile across the gap (residual or bypassed mud layers on the wall), instabilities due to density contrasts (Rayleigh–Taylor instability) and/or shear-rate contrasts (Kelvin–Helmholtz instability) and/or viscosity contrasts (Saffman–Taylor instability).

Here, we pursue the modeling approach developed in Bittleston et al. (2002), Pelipenko and Frigaard (2004a) and Pelipenko and Frigaard (2004b), whereby classical dimensional scaling methods are used to reduce the full three-dimensional equations of motion to a two-dimensional averaged model. We extend the models to include casing reciprocation and rotation as well as arbitrary casing eccentricity. The above work assumes flow symmetry along the vertical plan and vertical-only eccentricity. However, it is important to extend it to the more general case, not only because horizontal eccentricity occurs in the field, but also loss of flow symmetry is to be expected when unstable flow conditions are met (Tehrani et al., 1993). Additionally, we also restrict the use of the narrow gap approximation to the derivation of the momentum balance equation. Deriving the continuity equation and fluid transport equations without using the narrow-gap assumption allows us to achieve a perfect mapping of the actual annular geometry. New numerical resolution strategies are also developed to speed up computations.

2. The (2+1)D model

The model is developed in Appendix A and only the final equations are presented below. We consider the injection of multiple fluids into the annulus. Initially, the annulus is occupied by a given number of fluids with a known distribution. We denote n_f the number of fluids that are present at any time in the annulus during the pumping. Each fluid is identified by an index $i \in [1, n_f]$ and characterized by its density ρ_i. The volume fraction of fluid $i \in [1, n_f]$ at a given time and position in the annulus is denoted $\tilde{c}_i$. Each fluid is also characterized by its own set of rheological parameters, as will be detailed in Section 2.4.

We aim at tracking the fluids' volume fractions in time, along the annulus, axially and azimuthally, after averaging the volume fractions, the axial and azimuthal fluid velocities radially across the gap, for a given axial depth and azimuth (hence the (2+1)D nature of the model). Thus, the model calculates the time-evolution and distribution of the gap-averaged volume fractions, using n_f fluid transport equations, the gap-averaged axial and azimuthal velocities and the pressure along the azimuthal-axial plan formed by the annulus using a single elliptic pressure equation.

2.1. The model assumptions

The use of this model is restricted to laminar flow (zero-th order approximation of the momentum balance equation) that is typically valid for narrow enough annuli. Examination of field conditions suggests that laminar flow and narrow-gap (see Eq. (4)) are the most common situations for primary cementing operations. This model is not expected to remain valid in the case of wider annuli (say $r_c/r_w \leq 0.8$ as found in Szabo and Hassager (1992), r_c and r_w being the casing and wellbore radii, respectively) and for turbulent flow. Wider annuli may be observed during other type of cementing operations, such as in remedial cementing where smaller pipe diameters are used to convey slurries. The model assumes that the temperature is constant in time and space. As fluid properties may vary with temperature, modeling their evolution during flow requires coupling the current flow model with the energy balance equation. It is expected that temperature distribution and evolution may significantly impact fluid properties in the field, and therefore fluid circulation patterns. For this reason, the above coupling is also being studied by the authors but, for the sake of clarity, it is not considered in the present model. Each fluid is assumed to be non-thixotropic. In reality, some completions fluids show thixotropy. One example is the setting of the slurry into cement. Drilling muds have also been reported as being thixotropic in Livescu (2012). Accounting for thixotropy remains a challenge as it requires that the shear history of the fluid is tracked.