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A 3D model for annular displacements of wellbore completion fluids with casing movement

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ABSTRACT

During mud circulation and cementing operations, non-Newtonian completion fluids are injected along the wellbore annular space formed by the gap between the outer wall of the casing and the rock face. During such processes, these fluids displace each-other and follow a complex path given by pressure gradients, rheology and density contrasts, casing rotation and reciprocation and by the actual shape and orientation of the annulus. Muds and cement slurries also often exhibit a yield stress which may represent additional challenge for optimal fluid removal and cement coverage. This paper presents a novel approach to solving the 3D flow and displacement of completion fluids in the annulus. In particular, this work extends a model published in Tardy and Bittleston (2015) which solves the flow in the 2D axial-azimuthal plane, to now capture fluid distribution and velocity profiles across the gap width in the 3D axial-azimuthal-radial space. The new 3D model is derived using the so-called narrow-gap approximation for the momentum balance equations. This approximation provides a mean to solve the 3D velocity and concentration fields while solving a 2D-only elliptic pressure equation, which is significantly faster to solve than the original 3D pressure equation, and without suffering any significant loss of accuracy.

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. In order to achieve optimum cement coverage, no mud should be left in the annular space as cement may not set along mud channels, and as a path might be left behind the casing that the formation fluids may follow. By-passed mud may take the form of channels occupying the entire annular gap in some parts of the wellbore, typically along the narrow part of the annulus where the casing is off-centered. Additionally, static mud layers may also be left along the annular walls in places where wall shear-stresses have not been sufficiently large to fully displace the mud. Formation fluid migration along the annulus 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.

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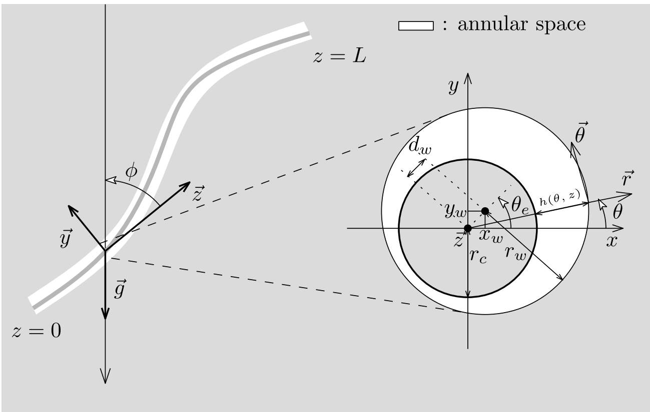

Fig. 1. Schematic of the annular space geometry and geometrical variables.

A review of previous studies of the annular flow of visco-plastic fluids has been published in the introduction of Tardy and Bittleston (2015). Their work consisted in extending the functionalities of the models developed in Bittleston et al. (2002), Pelipenko and Frigaard (2004a, 2004b). In these studies, classical dimensional scaling methods are used to reduce the full 3D equations of motion to a 2D gap-averaged model. The resulting models are indeed 2D ones or, more precisely, (2 + 1)D models considering that the radial dimension (the dimension that goes from the casing wall to the rock face) is not neglected but averaged. As a result, these models solve the flow in the axial-azimuthal plane using gap-averaged fluid properties such as concentration, friction factor, velocity, and density. In Tardy and Bittleston (2015), the possibility to simulate casing rotation and reciprocation as well as arbitrary casing standoff and standoff orientation was added to previously published models. It was then showed that the model could capture complex and relevant flow patterns often observed when fluids have rheological properties and/or density contrasts, and when the casing is off-centered and moved during the flow.

One missing capability of the model presented in Tardy and Bittleston (2015) and the previous art is the determination of the fluid velocity and fluid concentrations profiles across the gap. Indeed, in their models, velocities and concentrations are averaged in the radial dimension, resulting in a flat velocity profile and a fully mixed fluid mixture across the gap. In reality, as one fluid displaces another, the fluid-fluid interface across the gap is rarely flat, and some displaced fluid may be by-passed by the displacing one in the central part of the gap. If the displaced fluid is viscous enough, residual layers may subsist for some time along the annular walls. It may be important to predict such situations when trying to optimize mud displacement. Also, when the casing is moved, a non-constant velocity profile is created across the gap. For instance, when the casing rotates more fluid is dragged with the casing near the casing wall than near the rock face promoting the spread of the fluid-fluid interface. With the new model presented here, such situations may now be predicted.

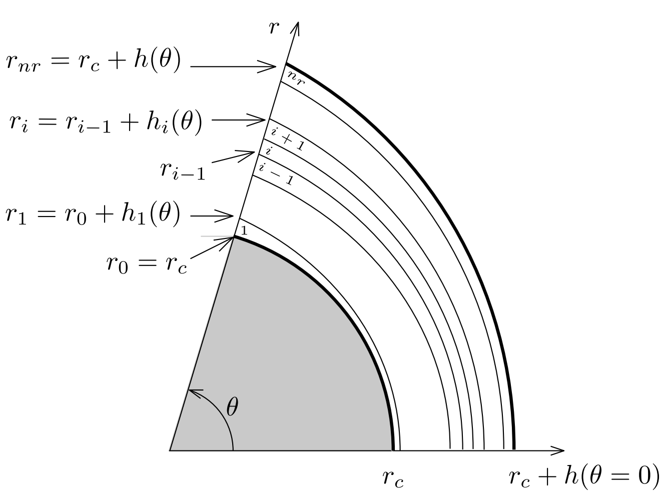

Fig. 2. Schematic of the annular domain decomposition into n_r layers for a given z.

Table 1
Flow parameters for Fig. 3.

Experiment	A1	A2
Bn	0	0
Rv	0.971	0.926
ε	1.19	0.992
e	0.5	0.8
n	1	1

The new model builds on the model presented in Tardy and Bittleston (2015) and extends its capabilities by not relying on the gap-averaging of the fluid properties. The new model still relies on the so-called narrow-gap approximation which allows us to solve the 3D velocity and concentration profiles while solving a 2D-only elliptic pressure equation. This simplification has a significant impact on the possibility to solve true 3D flow patterns in a reasonable amount of time. Indeed, solving the original 3D non-linear elliptic pressure equations remains far too much time-consuming when considering realistic situations with sufficiently high resolution levels, the current computing powers and the time a field engineer can spare for simulating an actual cementing job. A similar philosophy was used in Wachs et al. (2009) to describe the flow of a single viscoplastic thyxotropic fluid in pipes. There, the authors also used the lubrication technique to extent their original 1D flow model to a 1.5D one where pressure is a function of the axial distance only (thus a 1D pressure) while fluid properties and axial velocity may vary radially (thus a 2D flow pattern).

2. The 3D 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 $k \in [1, n_f]$ and characterized by its density ρ_k. The volume fraction of fluid $k \in [1, n_f]$ at a given time and position in the annulus is denoted $\tilde{c}_k$. Each fluid is also characterized by its own set of rheological parameters, as will be detailed in Section 2.5. We aim at tracking the fluids' volume fractions in time, along the annulus, axially, azimuthally, and radially (hence the 3D nature of the model) Thus, the model calculates the time-evolution and distribution of the fluid's volume fractions, using n_f fluid transport equations, the axial, azimuthal and radial velocities in the axial-azimuthal-radial domain formed by the annulus. The pressure is solved using a 2D non-linear 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. (3)) 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