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Residual drilling mud during conditioning of uneven boreholes in primary cementing. Part 1: Rheology and geometry effects in non-inertial flows

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ABSTRACT

We perform a detailed computational study of the flow of a Bingham fluid along a narrow channel, with one locally uneven wall. This uneven section of the channel represents a washed out section of an oil well about to be cemented. By studying a wide range of different washout geometries, of differing shape characterized by dimensionless height h and length L, we discover that the flows exhibit a type of self-similarity in the limit of large h and B. More specifically, in this limit we find that regardless of the washout geometry, the area of the channel that contains moving fluid is the same for each L. Essentially, uneven and distant parts of the washout become full of static fluid, below the yield stress, while the flow self-selects its own unique geometry. The washout geometry with the largest flowing region within the washout, appears to be the square wave. We show how a simple correction can be calculated that allows one to predict the flowing area for other washout geometries. Lastly, we examine the effect on the pressure drop of different washout geometries.

1. Introduction

A crucial part of the primary cementing operation [1] is the removal of drilling mud from the annular space between casing and formation. This occurs during the fluid displacement (or cement placement) phase of the process, which is itself a complex flow not fully understood; see e.g. [2–4]. Prior to the fluid displacement phase, most service companies and operators recommend to pre-circulate the well, by pumping the drilling mud from the bottom to the top of the well at least once ("circulating bottoms-up").

The circulation phase has two main purposes. Firstly, drilled cuttings and other solids still in the well, which may have settled as the casing is run in to the borehole, are cleared from the flowpath. Secondly, the circulation serves to shear the mud and hence condition it prior to displacement. Depending on the operational circumstances and the type of drilling mud, the mud may have been static in the borehole for a period of hours before circulation. Over this time significant gel strengths may develop due to thixotropic effects. Simplistically speaking this gel strength is destroyed by shear, returning the drilling mud to its dynamic yield stress (which may still be significant).

Unlike drilling geometries, the annuli in primary cementing are relatively narrow. If the borehole is reasonably uniform, the flow is primarily in the axial direction and on each azimuthal section the largest shear stresses are found at the walls of the annulus. The wall shear stresses are smaller on the narrow side of the eccentric annulus. This means that there is a critical minimal pressure gradient that must be exceeded in order to mobilize the drilling fluid on the narrow side of the annulus; see e.g. [5–7]. Thus, stationary residual drilling fluid is an inherent part of flowing through irregular geometries.

A different type of irregularity occurs in poorly consolidated formations that may partially collapse during the drilling process. The resulting "washouts" (see e.g. Fig. 1) are geometrically dependent on both the drilling hydraulics and the local geology, hence unpredictable, although sometimes measured using a caliper. The effect on mud circulation of such geometries can however be guessed: for sufficiently deep washouts we expect the drilling mud to remain static within parts of the washout during the circulation operation. The objective of this paper is to begin to systematically study this phenomenon, with the aim of being able to offer quantitative predictions.

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We have not found any work that directly studies this problem. Three difficulties present themselves. First, the washout geometries are unpredictable and three-dimensional (3D), making analytical study difficult and computational study slow. Second, the critical feature of the yield stress in the drilling mud must be accounted for physically and computationally in a way that distinguishes slowly flowing regions from stationary regions. For example, slow flows past cavities of Newtonian fluids can yield arbitrarily slowly moving fluid, see e.g. [8]. Thirdly, a range of flows are experienced in cementing and drilling operations (see [1,9]), ranging from the breaking of circulation through to fully turbulent flows. Thus, at the outset it is necessary to focus in on specific flow types and make simplifications in order to make the problem tractable while still preserving some relevance. In this paper we study non-inertial Stokes flow solutions ($Re = 0$) past two-dimensional (2D) washout regions.

A number of authors have studied flow of yield stress fluids past cavities or expansions, either in 2D or axisymmetric geometries. Mitsoulis and co-workers (e.g. [10]) have studied both planar and axisymmetric expansion flows, over a wide range of Bingham and Reynolds numbers, showing significant regions of static fluid in the corner after the expansion. Flow of yield stress fluids through an expansion–contraction has been studied experimentally and computationally in [11–13]. In [11] Carbopol solutions were pumped through a sudden expansion/contraction, i.e. narrow pipe – wide pipe – narrow pipe. A range of flow rates were studied and the yield surfaces were visualised nicely by a particle seeding arrangement. Inertial effects are evident in asymmetry of the flow. For all the experiments shown, stagnant regions first appear in the corners of the expansion and for all the results shown there are stagnant regions. Comparisons are made between experimental and numerical results, which are at least qualitatively in agreement, see [11,12]. In [13] qualitatively similar computations are carried out, but using an elasto-viscoplastic model.

In our previous work we have studied flow along a symmetric 2D wavy channel. Firstly, we have studied small amplitude long wavelength perturbations from a uniform channel geometry; see [14,15]. The focus is on deformation and breaking of the central plug region. Secondly, in [16] we have studied larger amplitude perturbations, using a numerical method similar to that here. We have derived predictions for the onset of stationary fluid regions (*fouling layers*), which occurred always initially at the walls in the widest part of the channel, quantified in terms of a critical *slope* of the wall. The main difference between the present study and [16] is that, having noticed qualitative difference between smooth wavy walls and abrupt expansion–contractions, we now begin to consider geometric variability in a more systematic way, i.e. we aim to derive results that may be applicable to generic washout shapes.

An outline of our paper is as follows. In Section 2 we derive the general model and describe the four washout geometries that we study. We also present an overview of the computational method, targeted here at $Re = 0$. For the results we first present examples of typical variations in the velocity, unyielded plug boundaries and the stress components, for the four washout geometries as the depth is increased; see Section 3.1. This is followed by a more systematic study of geometry and yield stress effects in Section 3.2, focusing only on the plug regions. We show that the onset of stationary flow is more complex than suggested in [16], but in contrast for large enough amplitudes a type of similarity emerges between geometries as the flow self-selects the flowing area. Section 3.3 describes our analysis of this self-selection and how to predict the flowing area of the washout. In Section 3.4 we describe the effects of the washout on the pressure drop along the channel, in terms of a correction. The paper closes with a summary in Section 4.

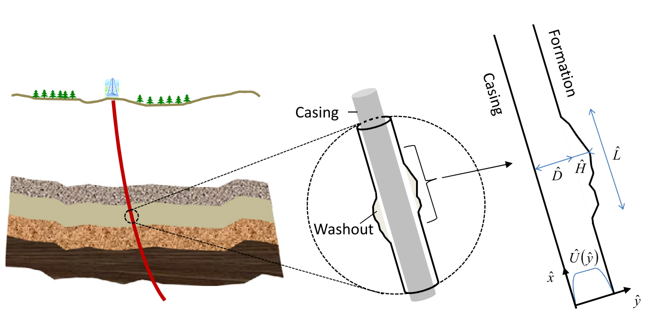

Fig. 1. Geometry of the washout in a section along the annulus.

2. A simplified washout model

Primary cementing circulation occurs through a long narrow eccentric annulus. In many situations, restrictions on frictional pressures limit the flow rates to the laminar regime, in which case the main velocity components are along the borehole axis, with azimuthal flows driven by slow axial variations in eccentricity. Supposing in this situation that we have a washout section, a reasonable simplification of the flow might be to consider a two-dimensional (2D) azimuthal-axial slice through the annulus; see Fig. 1. Neglecting azimuthal flow, the channel formed has an in-gauge width $\widehat{D}$ (dependent on the inner and outer diameters and the eccentricity), being bounded on the inside by the casing and on the outside by the formation.

The washout geometry is as yet unspecified, but in the 2D section described we will characterize the washout as having a length $\widehat{L}$ and a maximum amplitude $\widehat{H}$. Coordinates $(\hat{x}, \hat{y})$ are aligned along the channel and across the annular gap, respectively; see Fig. 1. Fluid circulates axially along the 2D section and we might assume a mean velocity $\widehat{U}_0$ in the $\hat{x}$-direction. As a typical width, $\widehat{D}$ is in the range 3–80 mm, the drilling mud may be considered as locally incompressible over the length of the washout, even for $\widehat{L}$ of the order of a few meters. A suitable model therefore is given by the Navier–Stokes equations for an incompressible viscous fluid. Non-Newtonian effects are significant and principal amongst these is the yield stress effect (at least for the flows we consider). The simplest rheological model containing a yield stress is the Bingham fluid. This model is also one that is used in drilling applications, although more complex models (e.g. Herschel–Bulkley) are also used. We use the Bingham constitutive model here, characterizing the fluid via its density $\hat{\rho}$, yield stress $\hat{\tau}_Y$ and plastic viscosity $\hat{\mu}$. Although a gross simplification, the key feature of yielding/not-yielding is captured by this model.

The Navier–Stokes equations are made dimensionless using $\widehat{D}$ and $\widehat{U}_0$ as length and velocity scales, respectively. Time is scaled with $\widehat{D}/\widehat{U}_0$, the shear stresses are scaled with $\hat{\mu}\widehat{U}_0/\widehat{D}$ and the static pressure is subtracted from the pressure before also scaling with $\hat{\mu}\widehat{U}_0/\widehat{D}$. The resulting equations are:

$$Re\frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\tau_{xx} + \frac{\partial}{\partial y}\tau_{xy}, \tag{1}$$

$$Re\frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\tau_{xy} + \frac{\partial}{\partial y}\tau_{yy}, \tag{2}$$

$$0 = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}, \tag{3}$$

where $\mathbf{u} = (u, v)$ is the velocity, p is the modified pressure and τ_{ij} is the deviatoric stress tensor. The constitutive laws are:

$$\tau_{ij} = \left(1 + \frac{B}{\dot{\gamma}(\mathbf{u})}\right)\dot{\gamma}_{ij} \iff \tau > B \tag{4a}$$

$$\dot{\gamma}_{ij}(\mathbf{u}) = 0 \iff \tau \leqslant B, \tag{4b}$$

where